Thesis

Reliability of radiological parameters for the determination of knee geometry during growth age

An analysis of interrater reliability in magnetic resonance imaging

submitted by

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Graz, 26.05.2025 Jakob Holzer m.p.

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To my astonishing girlfriend, thank you from the bottom of my heart. Your love and unwavering support have meant everything to me throughout the last years. I am truly grateful for everything you've done.

Zusammenfassung

Zuverlässigkeit radiologischer Parameter zur Kniegeometrie im Wachstumsalter

Einleitung:

Die rezidivierende Patellaluxation ist eine häufige Pathologie des Kniegelenks und tritt meist im Alter von 10-20 Jahren auf. Die Luxationsneigung ist durch Veränderungen der Morphologie des Knies (Trochleadysplasie, Patella alta, Lateralisation der Tuberositas tibiae) bedingt und wird durch bestimmte Parameter erhoben. Diese Arbeit untersucht die Interrater-Reliabilität dieser Parameter bei Patient*innen unter 18 Jahren.

Methodik:

Für 50 zufällig ausgewählte Patient*innen unter 18 Jahren mit einer Patellaluxation in der Krankengeschichte wurde die Reliabilität ausgewählter Parameter mithilfe von Cohen's Kappa und der Interklassenkorrelation angegeben. Dafür wurden jeweils 25 MRT-Bilder von zwei verschiedenen Untersucherpaaren vermessen.

Ergebnisse:

Die Trochleadysplasie wurde mit der Dejour-Klassifikation (Cohen's Kappa: 0,785) sowie den Parametern Trochlear Sulcus Angle (ICC: 0,759), Trochlear Depth (ICC: 0,702) und Lateral Trochlea Incilnation Angle (ICC: 0,826) evaluiert. Diese Parameter zeigten alle eine exzellente Reliabilität. Die Messung der axialen Position der Patella mit den Parametern Lateral Patellar Displacement (ICC: 0,781), Patellar Tilt (0,918), Angle of Fulkerson und Laurin (ICC: 0,914/0,89) zeigte ebenfalls exzellente Reliabilität. Der mediale und laterale Facet Angle of Cartilage der Patella (ICC: 0,496/0,723) waren mittelmäßig zuverlässig zu messen. Bei der Bestimmung der Lateralisierung der Tuberositas tibiae zeigte sich eine exzellente Reliabilität für die Tibial Tuberosity to Trochlear Groove Distance (TT-TG: ICC: 0,792) bzw. eine gute Reliabilität für die Tibial Tuberosity to Posterior Cruciate Ligament Distance (TT-PCL: ICC: 0,725). Die sagittale Patellaposition wurde mit dem Canton-Deschamps-Index (ICC: 0,533) und dem Patellotrochlear-Index (ICC: 0,792) vermessen.

Diskussion:

Besonders geeignet für Patient*innen unter dem 18. Lebensjahr scheinen aufgrund der hohen Reliabilität die Parameter Dejour Klassifikation und Lateral Trochlea Inclination Angle für die Trochleadysplasie, der TT-TG Abstand für die Lateralisation der Tuberositas tibiae sowie der Patellotrochlear Index für die sagittale Positionierung der Patella zu sein. Für die Bestimmung der axialen Position weisen alle Parameter (LPD, TILT, FULK und LAUR) eine gute Eignung auf.

Abstract

Introduction

The recurrent patellar dislocation is a common pathology of the knee joint and usually occurs at 10-20 years of age. It is caused by changed knee morphology (trochlear dysplasia, patella alta, lateralisation of the tibial tubercle) and evaluated by certain parameters. This thesis investigates the inter-rater reliability of those parameters in patients under 18 years.

Materials and methods

For 50 randomly selected patients under 18 years with a history of patellar dislocation the reliability of specific parameters was noted using Cohen's kappa and the intraclass correlation coefficient. Therefore, two pairs of observers measured the parameters in 25 MR images each.

Results

The trochlear dysplasia was evaluated using the Dejour classification (Cohen's kappa: 0.785), the Trochlear sulcus angle (ICC: 0.759), the Trochlear depth (ICC: 0.702) and the Lateral trochlea inclination angle (ICC: 0.826). All these parameters were excellently reliable. The measurements regarding the axial position of the patella showed excellent reliability (Lateral patellar displacement: 0.781, Patellar tilt: 0.918, Angle of Fulkerson/Laurin: 0.914/0.89 (ICC)). The medial and lateral facet angle of cartilage of the patella (ICC: 0.496/0.723) proved moderately reliable. The evaluation of the lateralisation of the tibial tubercle showed excellent (TT-TG: 0.792 ICC) and good (TT-PCL: 0.725 ICC) reliability. The sagittal patella position was measured using the Canton-Deschamps index (ICC: 0.533) and the Patellotrochlear index (ICC: 0.792).

Discussion

Due to their high reliability, the Dejour classification and the Lateral trochlea inclination angle were particularly suitable for the evaluation of trochlear dysplasia, the TT-TG distance for the lateralisation of the tibial tubercle and the Patellotrochlear index for patella alta. For the axial position of the patella all examined parameters (LPD, TILT, FULK and LAUR) were well suited.

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List of Abbreviations

CDI	Caton-Deschamps index
CT	Computed tomography
DICOM	Digital Imaging and Communications in Medicine
FULK	Angle of Fulkerson
ICC	Intraclass correlation coefficient
LAUR	Angle of Laurin
LFAC	Lateral facet angle of cartilage
LPD	Lateral patellar displacement
LPFL	Lateral patellofemoral ligament
LPML	Lateral patellomeniscial ligament
LPTL	Lateral patellotibial ligament
MDC	Minimal detectable change
MeSH	Medical Subject Headings
MFAC	Medial facet angle of cartilage
MPFL	Medial patellofemoral ligament
MPML	Medial patellomeniscial ligament
MPTL	Medial patellotibial ligament
MRI	Magnetic resonance imaging
PFI	Patellofemoral instability
PTI	Patellotrochlear index
SPECT- CT	Single-photon emission computed tomography
TILT	Patellar tilt
TT-TG	Tibial tuberosity to trochlear groove (distance)

TT-PCL	Tibial tuberosity to posterior cruciate ligament (distance)
VL	Vastus lateralis muscle
VM	Vastus medialis muscle
VMO	Vastus medialis oblique/obliquus muscle

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1 Introduction

This thesis focuses on the radiological evaluation of risk factors causing patellofemoral instability (PFI), which is characterized through recurring dislocations or subluxations of the patellar bone out of the trochlear groove (1). It is a complex disorder caused by an insufficiency of bony, muscular and soft tissue restraints preventing the patella from sliding out of the trochlear groove (2, 3).

The patellar dislocation is the acute event of displacement of the patella out of the trochlear groove. The majority of patellar dislocations occur in the context of sporting activity or trauma (4, 5). The most common mechanism of injury is the impact of an indirect force leading to valgus stress on the flexed knee in combination with an externally rotated tibia (5, 6). However, it is highly unlikely to have a patellar dislocation without abnormalities of the patellofemoral anatomy (5).

Due to lateralizing forces resulting from the quadriceps alignment the majority of dislocations are oriented towards the lateral side (7).

1.1 Aetiology

When the patella dislocates due to a traumatic injury and without predisposing risk factors, it is classified as a traumatic dislocation (8). Most commonly the dislocation occurs in adolescents or young adults during sporting activity (4). However, this pattern of injury accounts only for a minority (5-7%) of dislocations (9).

The recurrent dislocation is the most prevalent and least severe type of dislocation. The onset of the instability is mostly in or slightly before adolescence and is typically marked by an acute initial dislocation during physical activity (8). Without surgical treatment up to 36-44 percent of patients will develop chronic instability, which may present as recurrent dislocations or subluxations occurring with minor trauma as well as anterior knee pain due to micro injuries and consequent inflammation in patella stabilizers (10, 11). Several morphological risk factors such as trochlear dysplasia, patella alta, patellar tilt or tibial tubercle lateralisation contribute to the severity of the disease (2).

Traumatic dislocations are mostly treated conservatively, whereas therapy options for recurrent dislocations include MPFL reconstruction and the correction of anatomical risk factors for patellar instability such as trochlear dysplasia, patella alta and lateralisation of the tibial tuberosity in order to restore the regular joint anatomy (10-12).

The congenital dislocation is especially rare and presents as a fixed knee flexion with an irreplaceable patella at birth. In contrast, the permanent dislocation is developed in the period from the first steps to the age of 5 (8).

The habitual dislocation presents itself as a dislocation at every knee flexion but with a normal patellar position in extension, whereas the habitual dislocation in extension is characterized by sub- or dislocation while the knee is extended with the patella returning into its regular position in flexion (8).

1.2 Patellofemoral anatomy

The patellofemoral joint is formed by the articular surface of the patella and the trochlear groove (13). The patella, the biggest sesamoid bone of the human body, is built into the tendon of the quadriceps muscle, where it increases the lever arm of the muscle to enhance its capability to extend the knee. In order to execute this function correctly, the patellar motion must be stabilized in the trochlear groove during flexion (14). The important stabilizers can be divided into static, passive and active (15).

Static stabilizers	Passive stabilizers	Active stabilizers
Bony and cartilaginous anatomy of the femoral trochlea	Medial patellofemoral complex (MPFL, MPML, MPTL, medial collateral ligament)	Quadriceps (VMO, VM, VL, Aponeurosis)
Bony and cartilaginous anatomy of the patella	Lateral patellofemoral complex (iliotibial band, LPFL, LPTL, LPML)	Hip and core muscles (secondary)
	Medial and lateral patellar retinaculum	
	Joint capsule	

Table 1: Important patellar stabilizers

This table lists the most important static, passive and active stabilizers of the patellar movement during extension and flexion (15).

The sliding surface of the patellofemoral joint is influenced by the morphology of the femoral trochlea and the patella. A deviation from the normal morphology destabilizes the joint (14). The lateral femur condyle is especially important as a static stabilizer restricting the lateral movement of the patella, as it is responsible for the first contact with the patella during increasing flexion and ensures the proper sliding of the patella into the trochlear groove (15).

The passive stabilizers include the patellar retinacula, the joint capsule and the medial and lateral patellofemoral complex, which consist of the medial and lateral ligaments overlying the knee (15). As part of the medial patellofemoral complex the medial patellomeniscal ligament, the medial patellotibial ligament and most importantly the medial patellofemoral ligament (MPFL) provide the highest resistance against a dislocation (16). The restraining force limiting medially orientated movement of the patella is produced by the iliotibial band, the quadriceps aponeurosis and multiple ligaments (15). Muscle fibres that originate from the vastus medialis muscle, called vastus medialis oblique muscle (VMO), serve as an active stabilizer against lateral dislocations (17). In addition, the patella also functions as a bony protection for the knee joint against traumatic injuries, centralises the forces of the different quadriceps parts and decreases the friction during knee movement (18, 19).

The most important structures of the patellofemoral joint and its stabilizers are described in more detail below.

1.2.1 Femoral trochlea

The femoral trochlea is located at the distal femurs forward facing joint surface. A sulcus covered by cartilage is formed between the lateral and medial femur condyle, which acts as a sliding surface and guidance for the patella during flexion (20). The cartilage coverage of the sulcus merges into the cartilage of the lateral and medial femur condyle and has a thickness of about 2-3 mm (21). The lateral condyle is more pronounced and proximally further extended than the medial and the depth of the sulcus forming the trochlear groove is increasing from proximal to distal (20, 21). The proximal start of this sulcus is slightly medial to the mechanical axis of the femur and proceeds in an oblique line from medial to lateral and then changes its direction to run towards the medial side (22). The angle formed by the two condyles of the femur and the trochlear sulcus is called trochlear sulcus angle and has on average 137 degrees (20).

Men have wider and higher condyles, whereas the female trochlea is wider and less deep (23).

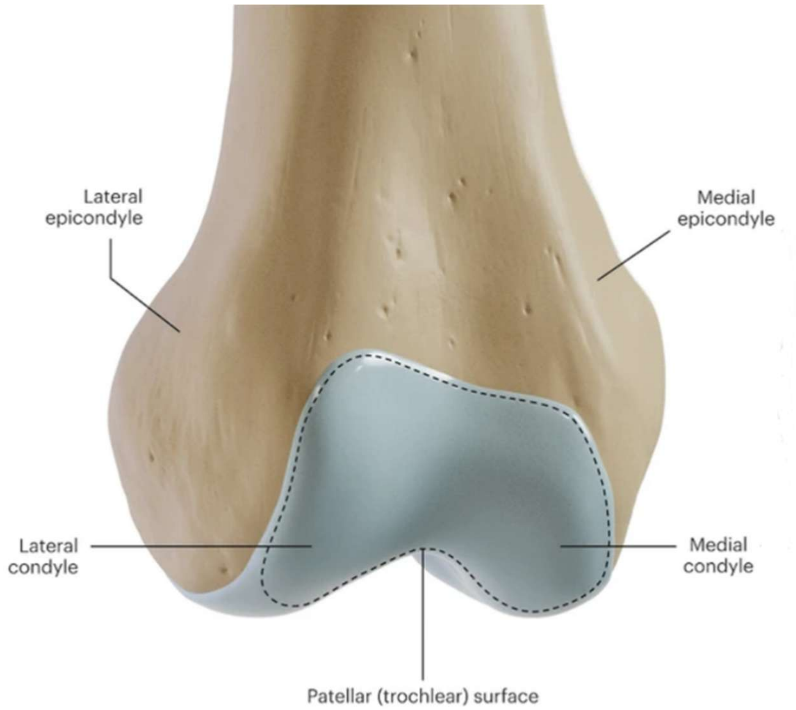


Figure 1: Anatomy of the distal femur. Adapted from (24)

The cartilage covered surfaces of the lateral condyle, the trochlear groove and the medial condyle (encircled area) form a bearing for sliding and guidance for the patella.

1.2.2 Patella

The proximal end of the patella, also known as the basis, is inserted by the quadriceps femoris muscle and the distal end, called the apex, attached to the patellar tendon (13). It has an oval to wedge-shaped form in the frontal plane (20, 21). On the posterior side the middle part of the patella forms the articular surface of the patella, the joint surface engaging with the femoral trochlea. The joint surface is covered by 4-5 mm of cartilage, which is separated by a ridge leading from proximal to distal into a medial and lateral facet (20). The facets create an angle of approximately 130 degrees (13). The medial facet is convex and smaller than the lateral facet, which is described as slightly concave. The distal and extra-articular end of the patella makes up a quarter of its length and connects the patella via the patellar tendon to the tibial tuberosity (20).

The articular surface can be further subdivided into seven facets: a superior, middle and inferior facet at both, the medial and lateral side and the odd facet. Located at the medial border of the medial facet the odd facet is separated by another much smaller ridge corresponding to the lateral border of the medial condyle and getting in contact with the medial condyle only in strong flexion of the knee (21, 25). The medial edge of the patella is thicker than the lateral and serves as a fixing point for the medial ligaments providing patellar stability (21). Anatomic variants of the patellar morphology are structured by the Wiberg-classification (25).

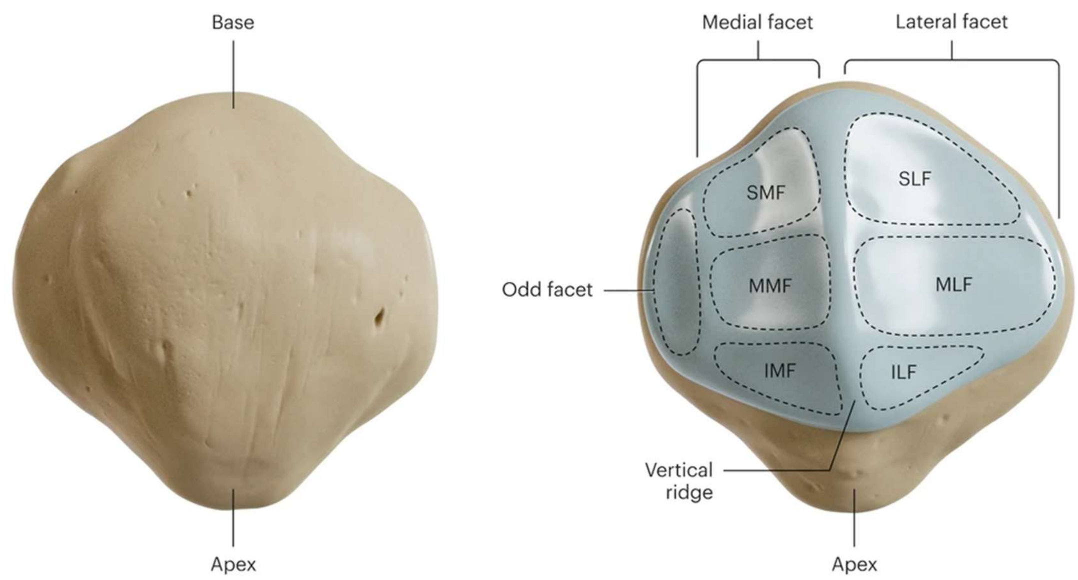


Figure 2: Anatomy of the patella. Taken from (24)

Left: Anterior view of the patella; Right: Posterior view of the patella with a depiction of the articular surface (blue). The articular surface is subdivided into the lateral and medial facet by a vertical ridge and each facet can be further divided into a superior, medial and inferior facet (Example: Superior lateral facet = SLF). An odd facet is found medial to the medial facet.

1.2.3 Ligaments and soft tissue

The soft tissue of the medial side of the knee is divided into three layers. The first and most superficial consists of the retinaculum patellae and provides minor stabilization for the patella. The middle layer is the most important for prevention of patellar dislocations and includes the medial patellofemoral ligament (MPFL), the patellotibial ligament and the medial collateral ligament. The innermost, third layer consists of the medial patellomeniscial ligament and the joint capsule (26).

The medial patellofemoral ligament is located between the medial side of the patella and the medial condyle. It has a mean length of 56 mm and is sail-like shaped with a patellar insertion about 20-30 mm and a femoral insertion approximately 10-22 mm wide (27). The femoral origin site is described to be in the area between the adductor tubercle and the medial epicondyle, whereas the other end of the ligament inserts into the upper and middle part of the medial patellar edge (26). Recent studies suggested the presence of fibres of the MPFL inserting into the quadriceps tendon, but there is disagreement whether these form a standalone ligament referred to as medial quadriceps tendon femoral ligament (28, 29). Additionally, there are ligament fibres connecting the MPFL to the aponeurosis of the VMO. This connection ensures that during the contraction of the quadriceps muscles, the MPFL can also participate dynamically in the stabilisation of the patella (29). Due to the great variability of the ligamentous fibres described, some authors summarise them as the patellofemoral complex (30).

The mean strength needed to tear the medial patellofemoral ligament is 208 Newton, even though the strength of ligaments varies a lot depending on age (31). It is responsible for more than 50 percent of the force resisting a lateral dislocation and a rupture of the ligament is present in 90 percent of lateral patellar dislocations (16, 26). A ruptured MPFL leads to a greater risk for future dislocations (26).

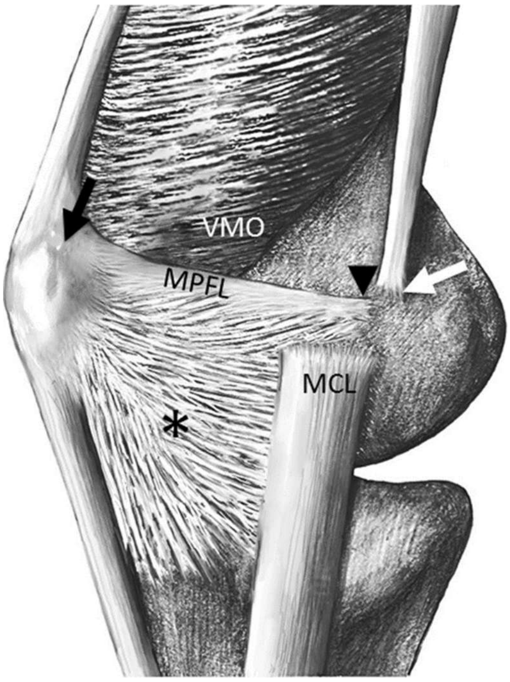


Figure 3: Anatomy of the medial patellofemoral ligament. Taken from (32)

Medial view of the knee. The MPFL elongates from the medial condyle (black triangle) to the medial side of the patella (black arrow). Fibres of the VMO insert into the MPFL and the medio-proximal edge of the patella. The medial patellar retinaculum is marked by an asterisk.

The medial patellomeniscial ligament (MPML) originates from the inferior pole of the patella and inserts into the anterior horn of the medial meniscus. It is located in the deepest layer of the soft tissue medial to the knee and is 20-40 mm long and 3-10 mm wide. The MPML combined with the medial patellotibial ligament contributes around 20-40 percent to the static force resisting lateral patellar dislocation (33).

The medial patellotibial ligament (MPTL) extends from the medial side of the inferior patellar pole to the tibia approximately 15 mm distal to the joint line and 15 mm medial to the patellar tendon (33).

The patellar ligament (patellar tendon) connects the distal two thirds of the front part of the patella to the tibial tuberosity, transmitting the forces of the muscular extensors from the patella to the tibia. In the area of the patella, the ligament is flat and wide and narrows towards the tibia (34).

In comparison to their medial counterpart, the importance of the lateral ligamentous structures for patellofemoral instability is reduced and less investigated. Siljander et al. (35) divided the lateral soft tissue into a superficial and deep retinacular layer. The superficial layer contains the iliotibial band, the vastus lateralis obliquus and the quadriceps aponeurosis. The deep retinacular layer includes deep fibres of the iliotibial band, parts of the quadriceps aponeurosis and in addition the lateral patellofemoral ligament, the lateral patellomeniscial ligament and the lateral patellotibial ligament. Both layers aim to prevent medial patellar dislocations with the deep layer being most effective at extension and the superficial layer at 30 degree of flexion (35).

1.2.4 Quadriceps

Localised at the front of the tight, the quadriceps femoris muscle is subdivided into four parts. The rectus femoris, the vastus medialis, the vastus lateralis and the vastus intermedius. These parts unite to form the quadriceps muscle tendon, which partly inserts into the patella and the tibial tuberosity (13). The functionality of the quadriceps concerns the extension of the knee joint as well as the flexion of the hip joint, whereas the latter is only performed by the rectus femoris. Therefore, the muscle is essential for posture, walking, balance and maintaining patellar stability (36).

Especially important for the dynamical stabilisation of the patella is the vastus medialis oblique muscle (VMO). The VMO represents the distal part of the vastus medialis and differs from the proximal vastus medialis longus by an increasingly oblique fibre course. The origin of the VMO extends from the linea aspera to the medial supracondylar line and inserts into the patella on its medio-proximal edge, the patellar tendon and the knee’s joint capsule. Due to this alignment, the VMO can stabilise the patella by contraction against lateral dislocation (37).

When compared to the vastus lateralis the vastus medialis is more pronounced, which is another factor resisting a lateral dislocation (37).

1.3 Epidemiology

The incidence of patellar instability depends on the factors age, sex, race and athletic participation (38).

For patellar dislocation several epidemiological studies provide data for an annual incidence ranging from 2.29 to 69.0 per 100,000 person-years, with an incidence of up to 108 per 100,000 person years in specific populations (females, age: 10-17 years) (38-42). Female patients account for about 60 percent of dislocations (43). The most injuries occur in boys and girls aged 14 to 18 and the incidence rate is rapidly decreasing after the age of 19 (39). About 52 percent of dislocations happen in the context of sporting activity and with a risk of about forty percent a patellar dislocation is followed by recurrent patellofemoral instability (38, 44). There is evidence for a familiar association and relation to specific genetic syndromes like Down syndrome (45).

1.4 Risk factors for patellofemoral instability

1.4.1 Trochlear dysplasia

By definition trochlear dysplasia is the malformation of the femoral trochlear groove concerning its depth and shape. The geometry of the trochlea is most important on its proximal end due to the extensive contact with the patella (46). Trochlear dysplasia was found to be one of the major risk factors for first time and recurrent patellar dislocations. The reported odds ratio regarding dislocation for patients with dysplasia is ranging from 7.7 to 61.9 when compared to individuals without dysplasia (47). The aetiology of trochlear dysplasia remains unclear. However, there are explanatory approaches regarding breech presentation, too little mechanical stress during development, genetic predisposition and maltracking of the patella (46).

There are various radiological parameters to assess trochlear dysplasia. A commonly used classification system is the Dejour classification, which was initially introduced as a tool to determine the severity of trochlear dysplasia on lateral radiographs and later adapted for CT and MRI imaging. The classification divides the dysplasia into four categories (A-D) but can be further simplified into a distinction of low (A & C or A & B) or high grade (B & D or C & D) dysplasia (48).

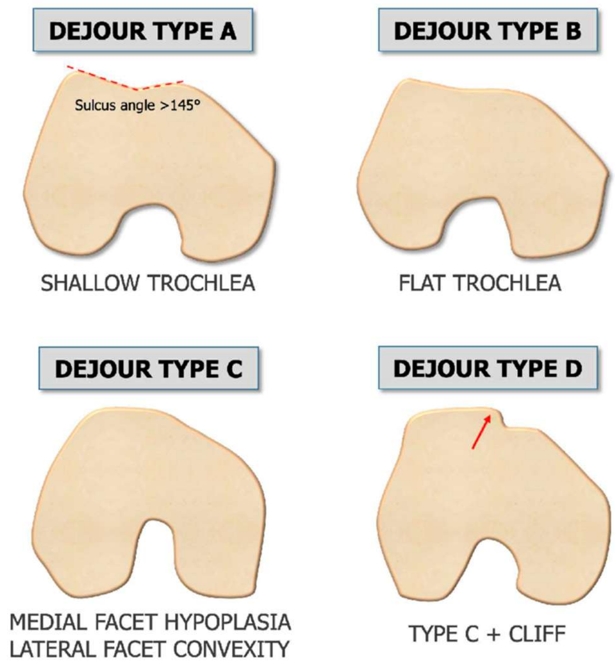


Figure 4: Dejour classification. Adapted from (49)

The Dejour classification is performed at an axial cross section of the distal femur. category A: A shallow trochlea with a sulcus angle > 145°; category B: Flat trochlea; category C: Medial facet hypoplasia with lateral facet convexity; category D: Characteristics of category C with an additional inclination (cliff).

Other recommended parameters are the trochlear depth, lateral trochlear inclination angle, trochlea bump, trochlear sulcus angle, trochlear facet asymmetry and ventral trochlea prominence (47, 50, 51).

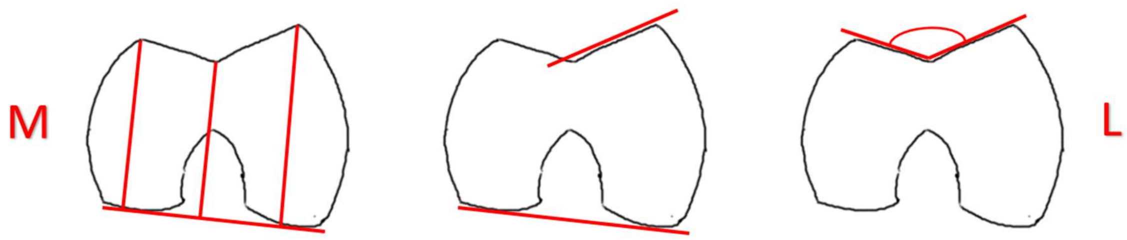


Figure 5: Radiological parameters of trochlear dysplasia

Radiological parameters for trochlear dysplasia used in this study. From left to right: Trochlear depth, Lateral trochlear inclination angle, trochlear sulcus angle. M = medial, L = lateral

The trochlear depth is calculated by subtracting the distance between the trochlea's deepest point and a posterior intercondylar line from the average distance of both condyles and the same posterior intercondylar line (52). A trochlea depth under 4 mm is considered pathological (53).

The lateral trochlear inclination angle is measured between a line along the lateral joint facet and a line connecting the most posterior margin of both condyles (54). This axial MRI parameter is used to specify the proximal trochlea, a key point in trochlear morphology. An angle under 11° is linked to PFI (54, 55).

The trochlear sulcus angle is the angle between the lateral and medial articular surface of the condyles intersecting in the trochlea's deepest point. The cut-off for a normal sulcus angle is 145-150° (53).

1.4.2 Patella alta

An abnormally large distance between the patella and the femur, the tibia or the trochlear groove is referred to as a patella alta. This positional anomaly results in reduced contact of the patella with the stabilising structures of the trochlea and therefore requires greater degrees of flexion for proper engagement of the articular surfaces. This leads to reduced stability during extension and lower degree flexion (56).

The majority of studies dealing with the risk factor patella alta conclude that there is a significant association between the presence of a high standing patella and patellar dislocations (47). The most commonly used measurements to determine patella alta include the Caton-Deschamps index (CDI), the Insall-Salvati ratio, the modified Insall-Salvati ratio, the patellotrochlear index (PTI) and the Blackburne-Peel ratio and are examined on lateral radiographs and MRI (55, 56).

The Caton-Deschamps index is particularly useful in the evaluation of knees within growth as it is measured from certainly ossified structures and is not influenced by deformities of the tibial tuberosity (57). Additionally, the Patellotrochlear index seems to be well suited during the growth period, as it addresses the configuration of the joints cartilage, which differs from the bony morphology. It must be determined on MRI (57, 58). The Insall-Salvati index can be difficult to assess in growth stages where the tibial tuberosity is not completely ossified (59).

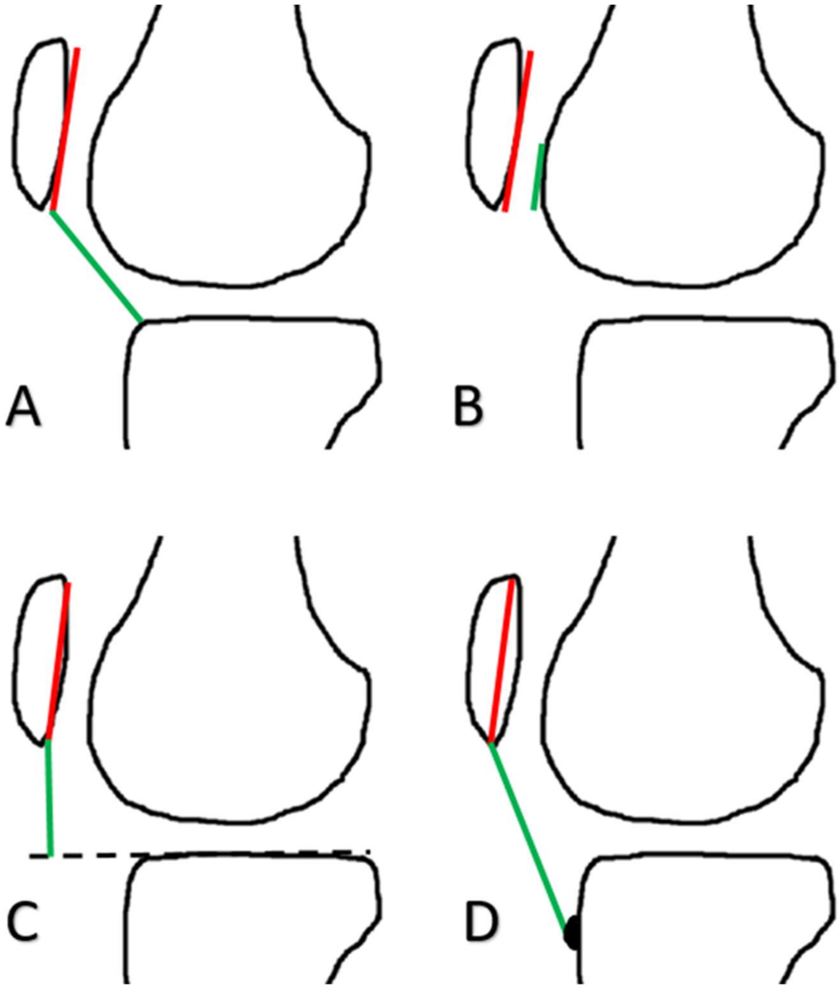


Figure 6: Radiological parameters of patella alta

A: Caton-Deschamps index; B: Patellotrochlear index; C: Blackburne-Peel ratio; D: Insall-Salvati ratio
The CDI is calculated as the relation of the distance from the tip of the patella to the anterior tibial plateau to the patellar cartilage (59).
The PTI is calculated by the relation of the patellar cartilage to the trochlear cartilage and its normal value is around 32% (58).

1.4.3 Genu valgum

Viewed in the frontal plane, the quadriceps muscle does not run in a straight line between its origin and the insertion of the patellar tendon. The patella deviates medially from this connecting line, which is why an angle can be formed between the patellar tendon and the connecting line between the midpoint of the patella and the anterior superior iliac spine. This angle is called the Q-angle (60). The valgus knee contributes to an enlarged Q-angle which is accompanied by an enhanced laterally directed force during extension that facilitates a patellar dislocation (57).

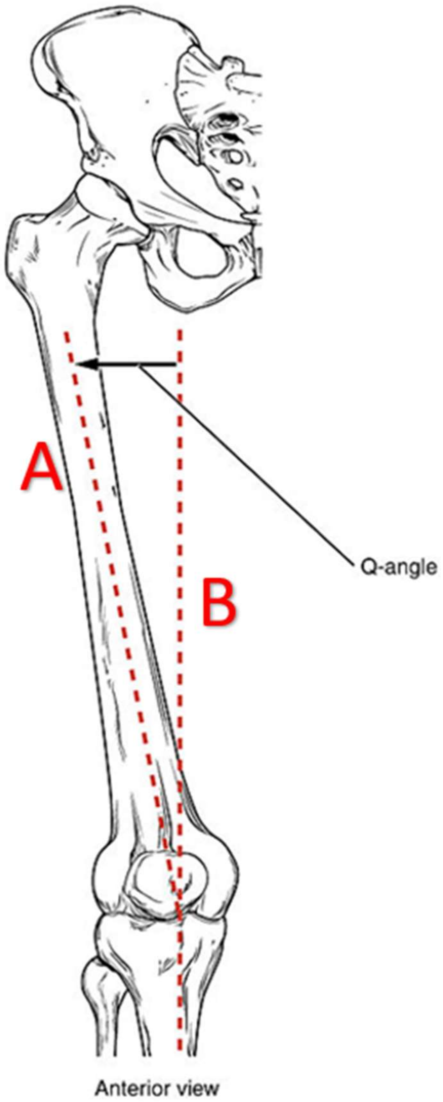


Figure 7: Q-angle. Adapted from (61)

The Q-angle is formed between the prolongation of the patellar tendon (B) and the line from the centre of the patella to the anterior superior iliac spine (A). Normal values: 10-15° for men and 15-20° for women (62).

Additionally, a higher Q-angle is associated with a lateral shift of the patella (63). Whether a high Q-angle is a standalone risk factor for PFI or just worsens the instability when combined with other risk factors remains unclear yet (62, 64).

1.4.4 Lateralisation of the tibial tuberosity

Another major risk factor for patellofemoral instability is an enlarged distance between the trochlea and the tuberosity of the tibia (65). As the patella is connected to the tibial tuberosity via the patellar ligament, a lateralisation of the tuberosity leads to a lateralised position of the patella (9). This lateralisation of the patella as well as the influence of the lateralised tuberosity on the Q-angle leads to an increase in the laterally directed force vector in extension (9, 57).

The lateralisation of the tibial tuberosity can also be caused by an increased external rotation of the tibia. The abnormal rotation of the tibia is associated with increased femoral antetorsion, which leads to a displacement of the rotational axis of the knee during walking and consequently to a valgic leg axis (66, 67). The most common radiological parameter for a correct evaluation of the lateralisation is the TT-TG distance followed by the TT-PCL and the TTTG index (9).

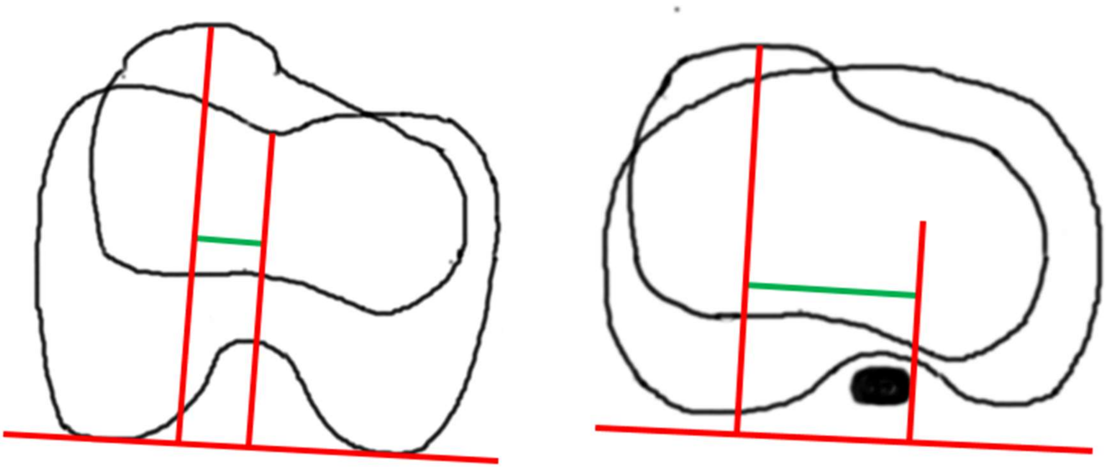


Figure 8: Radiological parameters of the lateralisation of the tibial tuberosity

Left: The tibial tubercle to trochlear groove distance elongates from the centre of the trochlear to the insertion of the extensors on the tibial tuberosity. A TT-TG exceeding 15-20 mm indicates malalignment (68).
Right: The TT-PCL is the distance between the tibial tuberosity and the medial edge of the posterior cruciate ligaments insertion into the tibia. It relies solely on the tibia and is independent from the joints flexion (68).

1.4.5 Distal malalignment and external tibial rotation

A complex risk factor is a malalignment or malrotation of the lower extremity, which can include an external torsion of the tibia, an internal torsion of the femur and external foot rotation. All these pathologies lead to an increased outward directed force on the patella that facilitates dislocations and often appear in combination (66, 67). The parameter used in this thesis to measure patellar misalignment is the lateral patellar displacement. Additional ones are the congruence angle, lateral shift or lateral patellar edge (51).

1.4.6 Patellar tilt and dysplastic VMO

An alteration in strength or arrangement of the quadriceps can cause pain and reduce patellar stability (69). Dejour et al. (65) found a dysplasia of the quadriceps present in 83% of their patients with recurrent dislocations. The radiological determination of a dysplastic quadriceps is made measuring the patellar tilt, with a value of >20° in extension indicating a dysplasia (65). However, the patellar tilt is also influenced by the morphology of the trochlea (4).

1.5 Biomechanics

The knee joint consists of the tibiofemoral and the patellofemoral joint. The function of both joint parts is important for movements of the lower limb during all sorts of activity and processing of emerging forces. Flexion and extension are rotations on a medial-lateral axis through the femur condyles and represent the most important movement of the tibiofemoral joint. The maximal extension is reached when the femur and tibia align in a straight line (0 to -5°), whereas the maximal achievable flexion is active 130° and passive 160° (70). In addition, when the knee is bent, internal (10°) and external rotation (40°) of the knee is possible (71).

The patellofemoral joint is frequently exposed to stress three times the body weight, which is why a solid stabilisation is necessary for the reliable execution of its function (72).

The change in the position of the patella during the movement of the knee joint is called patellar tracking (73). This motion depends mostly on the geometry of the patella and the trochlea and is subdivided into six parts: the proximal-distal translation, the anterior-posterior translation, the medial-lateral shift, the rotation, the flexion and the tilt. The shift of the patella is defined as its translation on the frontal plane and the patella's neutral position is set to be at 0° of flexion. From the neutral position to about 10-30° of flexion a slight medial shift was observed instantly followed by a lateral shift. At about 80° of flexion another medial shift was described in some knees. The patellar flexion (rotation of the patella on the medial-lateral axis) increases with progressing knee flexion but with a lower value of about 60-70 % of the value of the knee flexion. For tilt and rotation very heterogeneous and small movement observations were made. In early stages of flexion (to 10°) the patella rotates medially and within the progressing flexion starts to rotate laterally. The rotation through a longitudinal axis of the patella (tilt) is believed to be laterally directed (1-15,5°) (74). The proximal-distal translation expands over approximately 66 mm (14).

In order to assure correct patellar tracking several stabilising factors are crucial and their effectiveness during the flexion must be explained.

In the fully extended knee the patella is located in the centre or slightly lateral between the two condyles and proximal to the trochlea with no significant bony stabilisation. The patella is the most mobile in this position.
With increasing flexion, the lateral condyle engages with the lateral patella and by 30° flexion, both condyles articulate with the sesamoid bone. The congruency and the contact area of the joint increases further up to 90° of flexion and starts to decrease again in deep flexion, where the points of contact are only on the medial and lateral edge of the patella (18). It was shown that a flattened trochlea leads to a significant decrease in stabilization, especially in the range of 0-60° (75).

About 50-80 percent of the whole force counteracting a lateral dislocation are contributed by the MPFL (26). It is especially effective in early flexion (0-20°) and offers the least support in the range of 20-60° of flexion (26, 76). After a dislocation the MPFL is torn in the majority of cases (26).

The VMO effectively contributes dynamic stabilising surely from 0° to 15° and probably up to 90° of flexion. However, the stabilisation is achieved through a basic tension and an increase of quadriceps strength did not always improve the restraining capability (64).

Besides of its function as a bony protection for the knee joint the patella enlarges the distance between the quadriceps tendon and the joint and therefore increases the length of the quadriceps lever arm by 10-30% depending on the degree of flexion. Through the shared insertion of all quadriceps heads into the patella it is able to concentrate their efficiency (19). Due to the thick cartilage coverage the potential friction between the trochlea and the quadriceps tendon is reduced by the patella (18).

Compared to males, women tend to have smaller joint contact areas and higher contact pressures (77).

1.5.1 Mechanism of injury

In order to lead to a dislocation, one or more risk factors usually have to exist simultaneously. The more and more severe these are, the less force is required to dislocate the patella. A lateral deviation of the quadriceps “direction of pull” from the mechanical axis of the lower limb results in a laterally directed force pushing the patella to the side (See: Genu valgum). This force causes the patella to most likely dislocate laterally (7).

Biomechanical studies proved that the dislocation will typically take place at the early stage of flexion at approximately 20-30°, where the patella starts to shift laterally. The dislocation force has to surmount the soft tissue restraints, most importantly the MPFL (76). The MPFL restraint force is the weakest at 30-60° of flexion, which could contribute to the tendency to dislocation in early flexion stages (75, 76). In addition to the slight flexion, the contraction of the quadriceps and an external rotation of the tibia can result in an acute dislocation (76).

1.6 Differences between immature and mature knee joints

There are several notable differences between the knees of children and adults. Firstly, the growth plates responsible for 2/3 of the longitudinal growth of the lower limb are near the knee joint. Furthermore, children have a much higher joint laxity due to the immature capsule and ligamentous structures (78).

The cartilaginous coverage of the patella did not differ significantly in thickness between adults and children, whereas the cartilage at the lateral side of the trochlea, the lateral and medial condyle were thinner in adults (79).

Kim et al. (80) reviewed the differences of the osseous morphology by comparing several radiological parameters describing the morphology of the trochlea, the lateralisation of the tibial tuberosity and the height of the patella. They came to the conclusion that there is no significant alteration of morphology in relationship to age and physeal closure (80). This is consistent with our observations from our paediatric patient collective from which the sample of this thesis was selected. Additionally, the mass and strength of the muscles surrounding the knee joint are reduced in children and their neuromuscular activation is less efficient (81).

1.7 Radiological Parameters of PFI

Several radiological modalities are available for the examination of patellofemoral instability or dislocations including X-ray, MRI, CT and SPECT- CT (20). Static imaging provides insight into the morphology of the patellofemoral joint, whereas dynamic imaging can be used to display interactions of bony, ligamentous or muscular stabilizers and malalignment in different degrees of flexion (51).

A standard lateral X-ray can be used for the determination of the patellar height and the merchant view for trochlear morphology and patellar tilt. Magnetic resonance imaging and CT enable a cross-sectional assessment of the joint morphology. In contrast to the CT, the MRI is better suited to portray the cartilaginous joint surface as well as ligamentous, cartilaginous, capsular and bony damage resulting from a dislocation (51). Another reason for favouring the MRI is the radiation exposure of the CT examination, especially in children.

The evaluation of the imaging regarding the risk for recurrent dislocations is done using various radiological indices. The majority of the indices tries to quantify risk factors such as trochlear dysplasia, patellar height, lateralisation of the tibial tuberosity, patellar tilt and patellar lateralisation (51).

The most frequently used PFI-indices are listed in the following table:

Trochlear dysplasia	Patellar height	Patellar tilt	Patellar lateralisation	Tibial tubercle lateralisation
Dejour classification	Insall-Salvati ratio	**Patellar inclination angle (Patellar tilt angle)**	Congruence angle	**Tibial tubercle-trochlear groove distance**
Trochlear sulcus angle	Modified Insall-Salvati ratio	**Angle of Laurin (Lateral patellofemoral angle)**	Patella-lateral condyle	**Tibial tubercle-posterior cruciate ligament distance**
Trochlear facet asymmetry	**Caton-Deschamps index**	**Angle of Fulkerson**	Bisect offset ratio	Q-angle
Lateral trochlear inclination	Blackburne-Peel ratio	Tilting angle	**Lateral patellar displacement**	
Trochlea depth	**Patellotrochlear index**	Patellofemoral index	Patellar displacement	
Ventral trochlear prominence		Angle of Grelsamer	Lateral patellofemoral length	
			Patellofemoral axial engagement	
			Tangent offset	
			Lateral patellar edge	

Table 2: PFI Indices

This table displays frequently used Indices for the evaluation of patellofemoral instability. The Indices used in this study are highlighted. (51)

The Parameters medial facet angle of cartilage and lateral facet angle of cartilage are used to determine patellar morphology (82).

1.7.1 Reported inter-rater reliability

The following table consists of the previously reported data on the inter-rater reliability on the majority of the parameters in this study. It is based on a systematic review conducted by Geraghty et al. (55).

Parameter	ICC
Trochlear sulcus angle	0.69–0.95
Trochlear depth	0.69–0.93
Patellar tilt angle	0.65–0.97
Caton-Deschamps index	0.41–0.96
Patellotrochlear index	0.71–0.87
TT-TG distance	0.74–0.98
TT-PCL distance	0.74–0.95

Table 3: Inter-rater reliability.

This table lists the inter-rater reliability of radiological studies regarding PFI on MRI scans since 2010 (55).

Except for the Caton-Deschamps index (fair to excellent) every parameter showed good to excellent agreement.

The intra- and interobserver reliability for the four-type Dejour classification (A-D) is poor but can be improved by using the two-type classification (high-grade/ low-grade) (48).

The other parameter used in this thesis are lateral patellar displacement, angle of Fulkerson, angle of Laurin, patellar tilt, medial facet angle of the patella and lateral facet angle of the patella. The first four showed almost perfect inter-rater reliability (>0.94) (83). The medial and lateral facet angle of patella showed moderate to substantial reliability (82).

1.8 Aim of the study

Due to differences in cartilage content and osseous morphology the immature knee joint may be more difficult to assess with regard to predisposing factors of patella instability than the adult knee. A multitude of studies investigated the reliability of radiological parameters for patellofemoral instability in an adult population. However, there is still a lack of knowledge if their results can be transferred to a growing patient. The aim of the present study is to verify the objectivity and suitability of already established parameters of knee joint geometry in the treatment of paediatric patients and to identify the most appropriate parameters by statistically determining the inter-rater reliability.

2 Materials and methods

2.1 Literature research

The search for suitable English literature was carried out through PubMed and Google Scholar. References of appropriate articles were screened for further relevant information. Additionally, German literature was found by using ‘SpringerLink’.

The majority of the literature was sourced through PubMed. At first the headings of every chapter like ‘trochlear dysplasia’ or ‘biomechanics (of the patellofemoral joint)’ were processed by automatic term mapping and satisfactory results were saved. In a systematic approach the MeSH terms ‘Patellofemoral Joint’, ‘Patellar Dislocation’, ‘Joint Instability’, ‘Patellofemoral Joint’, ‘Patella’, ‘Femur’, ‘Patellar Ligament’, ‘Quadriceps Muscle’, ‘Biomechanical Phenomena’ were used. These terms were combined with appropriate subheadings for the corresponding chapters, such as ‘anatomy and histology’, ‘diagnostic imaging’, ‘growth and development’, ‘surgery’, etc. The Advanced Search Builder was used to gather recent literature without MeSH descriptors. The MeSH terms and subheadings mentioned above as well as the headings of the chapters were entered into the Advanced Search using various combinations and Boolean operators. The preferred article types were ‘Books and Documents’, ‘Meta-Analysis’, ‘Review’ and ‘Systematic Review’.

2.2 Study design

This is a monocentric, retrospective study conducted at the State Hospital Graz in collaboration of the departments for paediatric orthopaedics and paediatric radiology. The local hospital information system openMEDOCS (Steiermärkischen Krankenanstaltengesellschaft m.b.H.) was used to identify patients with at least one patellar dislocation treated from March 2000 to March 2021 at the department of paediatric orthopaedics. Radiographs and magnetic resonance images of the knee were retrieved from the hospitals picture archiving and communication system (PACS) (Institute of Medical Informatics, Statistics and Documentation - Medical University Graz) and the magnetic resonance images were reviewed by two senior medical students, a PhD student in medical science, two residents for orthopaedics and traumatology and two attending physicians for paediatric orthopaedics and one attending physician for paediatric radiology. The parameters of this study were selected with the aim of finding promising and well established parameters that are clinically suitable for the assessment of PFI in the paediatric patient population with its high cartilage content of the joint. MRI imaging was chosen for the evaluation due to the necessity to visualise ligamentous and cartilaginous structures as well as the common use of MRI in the diagnostic process of PFI. In order to determine the inter-rater reliability two pairs, each with one expert and one less experienced reviewer, evaluated the selected parameters independently in 25 MRI's per pair. These 50 images were selected randomly beforehand and the results were the subject to statistical analysis regarding the inter-rater reliability. The two orthopaedics and traumatology residents were appointed as experts. Two senior medical students were picked as the less experienced assessors.

2.3 Patients

After the approval form the local ethics committee the hospital information system (openMEDOCS) was screened for patients with the diagnosis of patellar instability or patellar dislocation. This way 648 patients were identified and their medical history was investigated for available imaging of the affected joint (radiographs and MRI).

The following criteria were used to select patients and MRI scans for evaluation:

<u>Inclusion criteria:</u>

- Age of the patient ≤ 18 years
- At least one patellar dislocation in medical history
- At least one magnetic resonance image available
- First available MRI after dislocation

Exclusion criteria:

- Age of the patient > 18 years
- Imaging after surgery for patellofemoral instability
- Patients with underlying diseases, syndroms, neuromusucular diseases, soft tissue diseases (Ehlers-Danlos syndrome, Marfan syndrome, Trisomy 21, etc.)

335 of these 648 patients met the criteria and subsequently the available images were analysed for those patients. Images within 6 months to a prior image were excluded from measurement due to the negligible changes in the joint geometry.

For the determination of the inter-rater reliability a random sample of 50 images was generated with Microsoft Excel. The sample size was determined by a recommendation of the institute for medical informatics, statistic and documentation of the medical university of Graz and verified by an online application developed by Mokkink et al. (84). Due to the specifications of the targeted ICC (see 2.6), an assumed high correlation and low to medium variance based on existing studies (55), the tool recommended a sample size of 40-50 images (84).

The approval for this study was granted by the Ethics Committee of the Medical University of Graz (ethics committee number 34-119 ex 21/22). As this was a retrospective study with pre-existing data, there was no need to obtain an informed consent form.

2.4 Data collection

The following data were extracted from the available images.

- Sex
- Weight
- Age
- Laterality
- Date of the MRI

The information for sex, weight and age were sourced automatically through the additional information in the DICOM data. The date of the MRI and the laterality was noted by the examiner. For twenty of the fifty included patients the MRI background information did not provide the weight. For this reason, the descriptive statistics for weight are limited to the available data.

The 15 parameters defined in chapter 2.5 were examined by the investigators using a DICOM-viewer. The exact procedure of measurement was done based on current publications: (52, 58, 59, 82, 85-88).
Our aim was to assess all 15 parameters for every available image. For the beginners a joint exercise was held in which the correct procedure of measurements was practised.

At the time of measurement, the investigators had access to the pseudonymized ID, the date of imaging and in some cases the laterality of the knee was reported. The results of the measurements from beginners and experts were entered in different tables.

The access to patient's history and imaging data was protected by the security precautions of the local hospital information system. After the identification of eligible patients, the retrieved DICOM-files were pseudonymized and available for evaluation through the password protected service Nextcloud (89). The access to the results of measurements was provided only for authorized personal.

2.5 Procedures of measurements

The exact procedure of measuring the different parameters in this study will be explained in detail below. The selection of the weighting (T1/T2) was mostly determined by the availability of the images.

2.5.1 Trochlear dysplasia

The assessment of trochlear dysplasia was based on the following parameters:

- Dejour classification
- Trochlear sulcus angle (TSA)
- Trochlear depth (TD)
- Lateral trochlear inclination angle (LTIA)

The Dejour classification categorised the dysplasia of the knee as N (None) when no signs of dysplasia were present or as A, B, C and D. The morphological criteria for classification into the different classes are shown in the following figure and the assessment was performed in the first axial plane with full cartilaginous coverage of the trochlea when scrolling from proximal to distal (85).

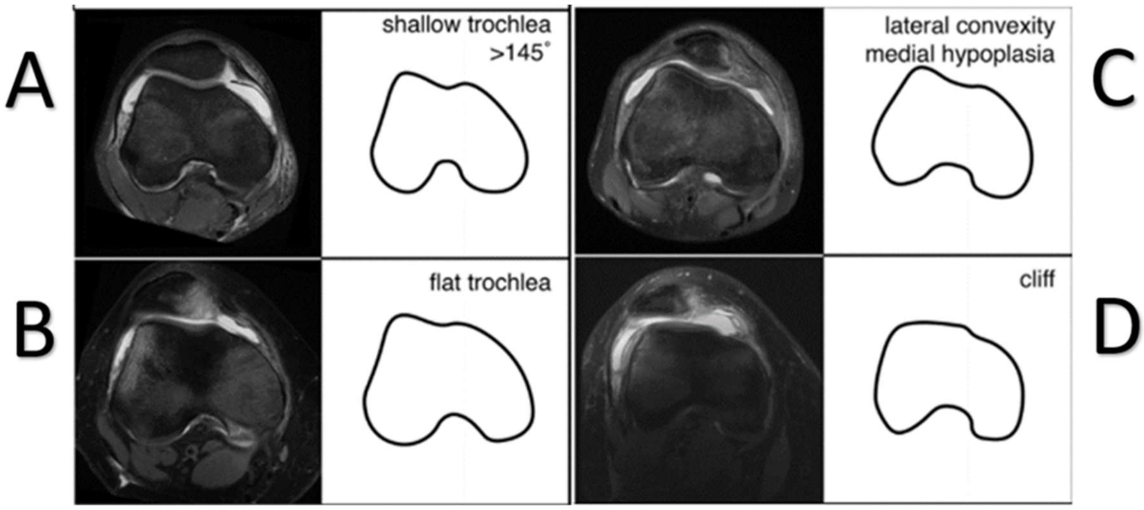


Figure 9: Dejour classification 2. Adapted from (85)

This figure describes the characteristics for the subclasses of the Dejour classification and showcases exemplary MRI scans.
Grade A: shallow trochlea with a TSA >145°
Grade B: flat/convex trochlea with reduced trochlear depth
Grade C: convex lateral facet and hypoplasia of the medial condyle
Grade D: asymmetric condyles with an inclination from the medial to the lateral condyle (cliff) (48)

The trochlear sulcus angle was measured in the axial plane with the greatest medial-lateral distance between the two epicondyles. The angle was measured by an electronic protractor between the lines form the deepest point of the sulcus to both most anterior parts of the trochlea margins (86).

For the measurement of the trochlear depth a tangential line through the posterior margin of the femoral condyles was drawn. From this line the perpendicular distance to the most anterior point of the lateral and medial trochlea facet as well as to the deepest point of the sulcus was measured. The distance of the posterior line to the sulcus was subtracted from the average of the distance from the line to the anterior facets. This was performed on the axial slice with the largest expansion of the femoral condyles (52).

The lateral trochlear inclination angle is defined as the angle between the posterior tangential line used for trochlear depth and the lateral trochlear facet (52).

Additionally, the width of the femur condyles (Condylar width) was determined in the axial plane with the widest distance between the lateral and medial margin of the condyles. The measured distance was the greatest possible distance between the margins.

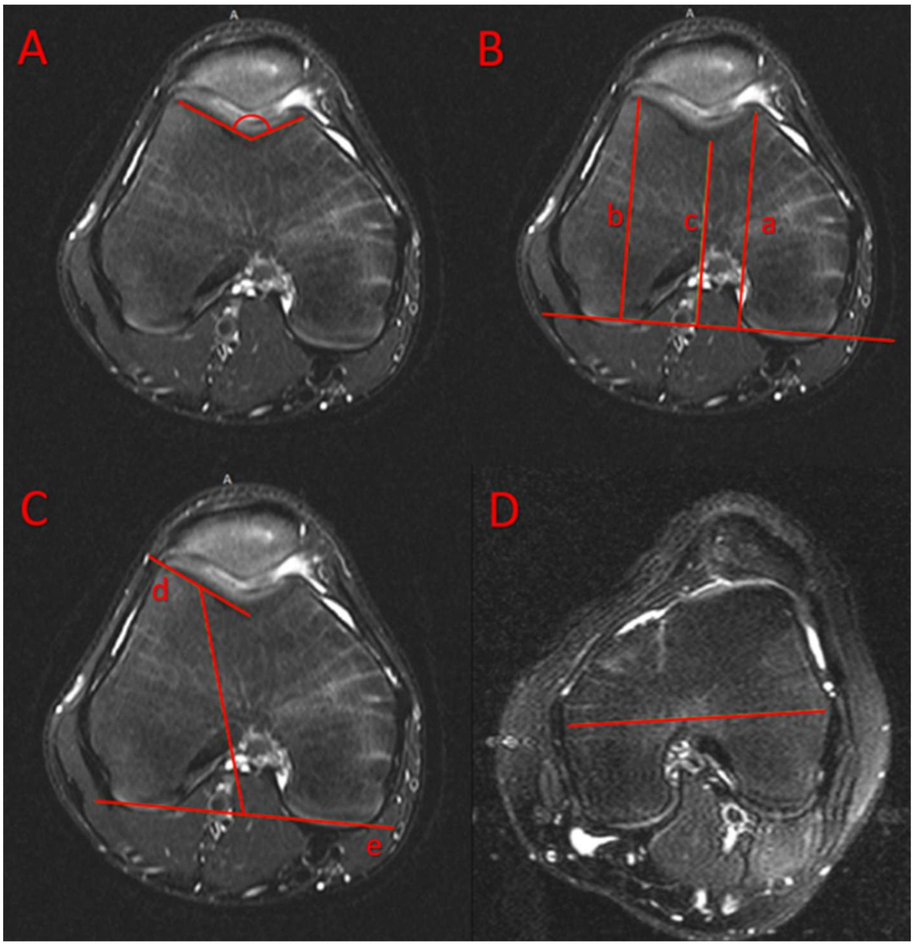


Figure 10: Exemplary measurements for trochlear dysplasia

A: Trochlear sulcus angle: The angle between the two lines from the most anterior parts of the medial and lateral trochlea to the deepest point of the femoral sulcus.

B: Trochlear depth: The sum of the anterior-posterior distance of the medial and lateral femur condyle (a,b) divided by two from which the distance from the femoral sulcus to the line connecting the posterior femoral margins (c) is deducted.

C: Lateral trochlear inclination angle: The angle between the lateral trochlea facet (d) and the line connecting the posterior femoral margins (e).

D: Condylar width: The distance from the lateral to the medial margin of the femur.

2.5.2 Axial patellar position and morphology

The axial position of the patella in relation to the femoral aspects of the knee joint and the morphology of the patellar facets was described using these parameters:

- Angle of Fulkerson
- Angle of Laurin (Patellofemoral angle)
- Patellar tilt (Patellar inclination angle)
- Lateral patellar displacement
- Medial facet angle of cartilage
- Lateral facet angle of cartilage

The angle of Fulkerson is formed by the line connecting the posterior condyles and the patella's lateral facet. Whereas the angle of Laurin was measured between a tangential line connecting the two anterior condylar surfaces and the patella's lateral facet. Booth angles were considered positive when the angle opened laterally (87, 90).

The patellar tilt angle was evaluated as positive when the angle between the line connecting the posterior condyles and the transverse patellar axis opens towards medial (87).

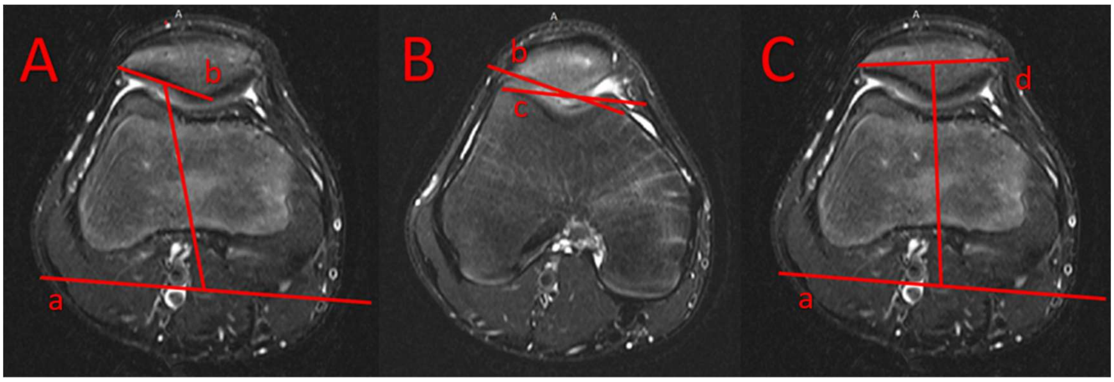


Figure 11: Exemplary measurements of Angle of Fulkerson, Angel of Laurin and Patellar inclination angle

A: Angle of Fulkerson: The angle between a line connecting the posterior condyles (a) and the lateral patellar facet (b).

B: Angle of Laurin: The angle between a tangential line through the anterior condyles (c) and the lateral patellar facet (b).

C: Patellar tilt: The angle between a line connecting the posterior condyles (a) and the transverse patellar axis (d).

Furthermore, the shortest extend of the distance between the lateral margins of the trochlear and the patellar facet was noted as lateral patellar displacement (87). This parameter was measured in the axial slice with the greatest medial-lateral distance through the patella.

The medial facet angle of cartilage (MFAC) as well as the lateral facet angle of cartilage (LFAC) were assessed in the axial MRI slice with the greatest medial to lateral expansion of the patella. The measurement of the MFAC was conducted between the line through the most medial and lateral point of the patella and the chondral surface of its medial side. The LFAC was measured between the same line through the most medial and lateral point of the patella and the chondral surface of its lateral side (82).

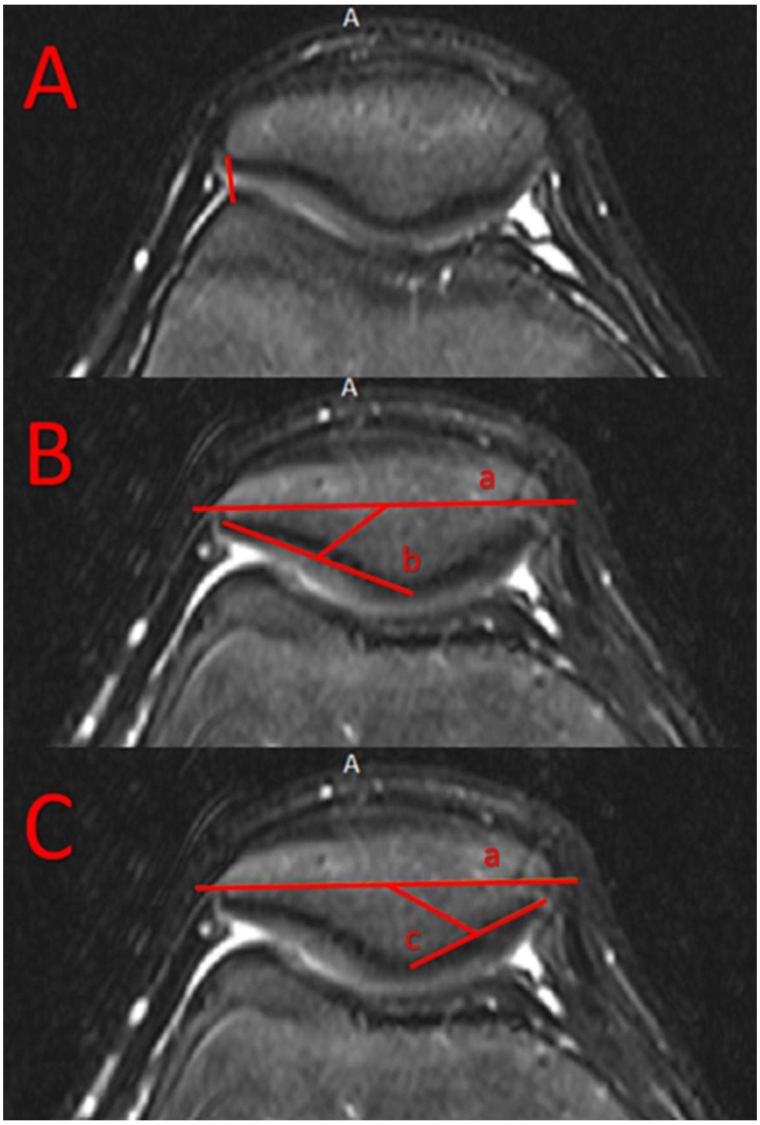


Figure 12: Exemplary measurements of Lateral patellar displacement, Lateral facet angle of cartilage and Medial facet angle of cartilage

A: Lateral patellar displacement: Shortest distance between the patellar facet and the lateral trochlear top.

B: Lateral facet angle of cartilage: Angle between the mediolateral patellar axis (a) and the lateral patellar facet (b).

C: Medial facet angle of cartilage: Angle between the mediolateral patellar axis (a) and the medial patellar facet (c).

2.5.3 Sagittal patellar position

The sagittal position of the patella was determined by using:

- The Caton-Dechamps index
- The Patellotrochlear index

For the CDI the length extending from the distal part of the patellar articular cartilage to the anterior-superior tibial joint surface (A) was divided by the extend of the patellar cartilaginous articular surface (B). CDI = A/B. This was carried out in the sagittal slice with the greatest patellar length (59).

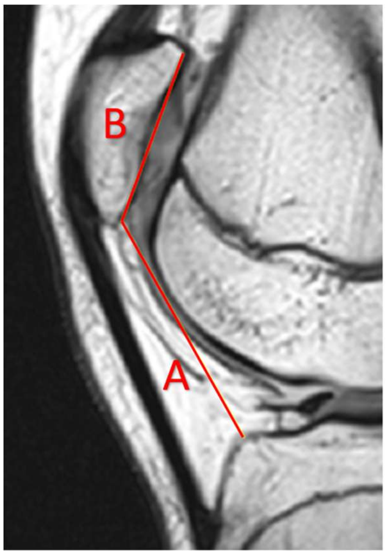


Figure 13: Caton-Dechamps index

For the calculation of the CDI the distance between the most distal point of the patellar and the most proximal and anterior point of the tibia (A) is divided by the sagittal extend of the patellar cartilage (B).

The PTI was noted as the percentage of the greatest sagittal expansion of patellar cartilage (Baseline patella) in relation to the distance of the superior aspect of the trochlear cartilage to the point of the trochlea at the same height as the lowest point of the patellar cartilage (Baseline trochlea). (PTI=Baseline trochlea/Baseline patella) (58).

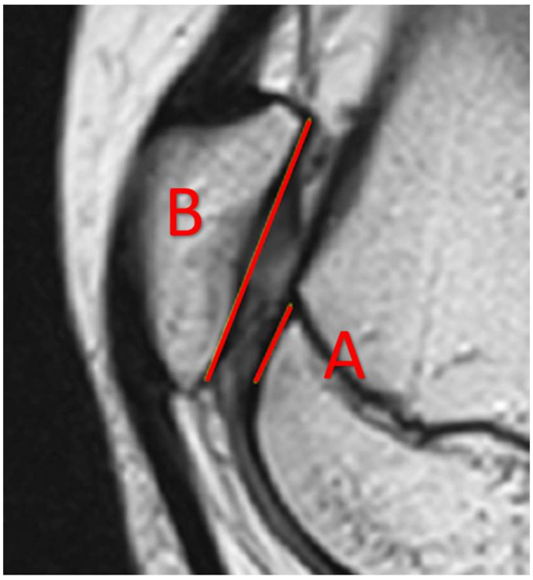


Figure 14: Patellotrochlear index

This figure shows the calculation of the PTI. The distance from the highest point of trochlear cartilage to the point where a horizontal line through the lowest part of the patella meets the trochlea (A) is divided through the longest sagittal distance for the patellar cartilage (B).

2.5.4 Lateralisation of the tibial tuberosity

For the evaluation of Lateralisation of the tibial tubercle the TT-TG and the TT-PCL distances were determined.

The tibial tubercle-trochlear groove distance (TT-TG) was measured as perpendicular distance from the vertical line through the deepest point of the sulcus (see trochlear depth) and the tibial tuberosity (52, 80).

The measured perpendicular distance between the medial border of the posterior cruciate ligaments (PCL) insertion into the tibia and the tibial tubercle was noted as Tibial tuberosity–posterior cruciate ligament distance (TT-PCL). In contrast to the TT-TG, the line through the posterior aspect of the condyles was not used, but rather a line orientated along the posterior surface of the proximal tibia (68, 88).

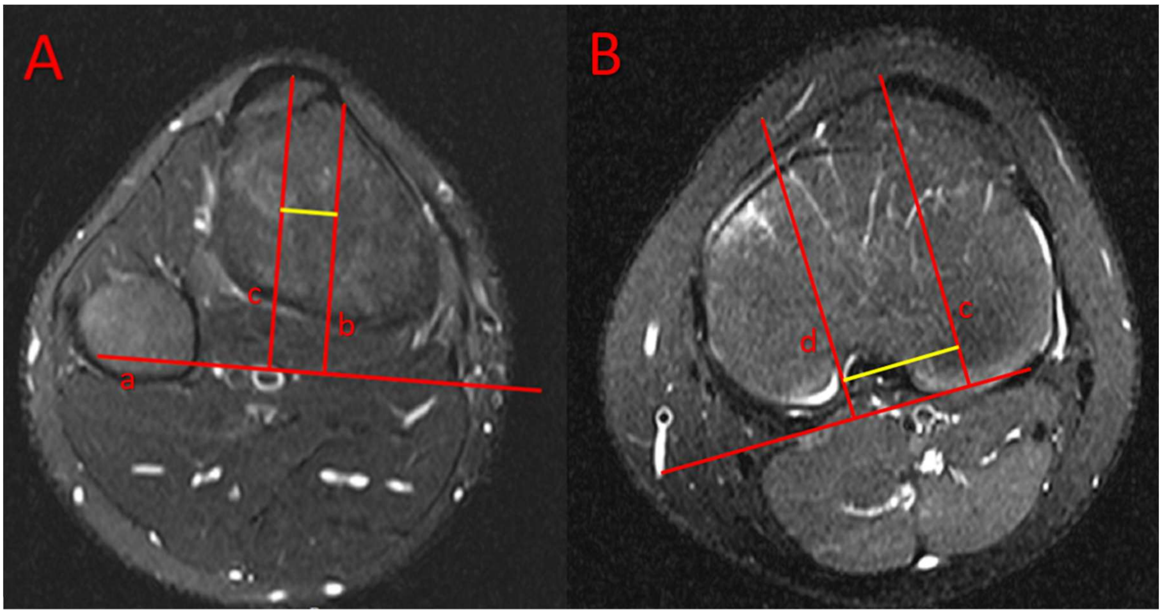


Figure 15: Exemplary measurement of TT-TG and TT-PCL

A: TT-TG: A line connecting the posterior condyles was drawn (a). Perpendicular to this line one line was laid through the deepest point of the sulcus (b, see: trochlear depth) and another line through the tibial tuberosity (c). The distance between those lines corresponds to the TT-TG distance.

B: TT-PCL: For the measurement of the TT-PCL an additional line was drawn through the most medial aspect of the PCL's insertion into the tibia (d) and the distance between line c from the TT-TG distance and d was recorded. The TT-PCL is measured parallel to a line along the posterior tibia.

Parameter	Source
Dejour classification	Stepanovich et al. (85)
TSA	Toms et al. (86)
TD	Kim et al. (52)
LTIA	Kim et al. (52)
Angle of Fulkerson	Charles et al. (87)
Angle of Laurin	Charles et al. (87)
Patellar tilt angle	Charles et al. (87)
LPD	Charles et al. (87)
MFAC/LFAC	Jimenez et al. (82)
TT-TG	Kim et al. (52)
TT-PCL	Mistovich et al. (88)
CDI	Paul et al. (59)
PTI	Biedert et al. (58)

Table 4: Sources for the procedure of measurement of the parameters used in this study

We aimed to reproduce the exact measurement methodology from the sources listed in this table.

2.6 Statistical evaluation

For the random sample the available baseline characteristics sex, age, weight and laterality of the image the following descriptive values were evaluated: Mean, Standard deviation, Median, Minimum, Maximum and Range.

The evaluation of the inter-rater reliability will be used in order to quantify the degree of agreement on given PFI parameters between experts and beginners. Different approaches were used to determine the reliability due to the nominal and metric scaling. The pairing of observers was constant. Every pair evaluated 25 images each.

The Dejour Classification with the possible outcomes of N (none), Grade A-D or alternatively high and low grade dysplasia is ordinal scaled.

The other parameters are measured in degrees (TSA, LTIA, FULK, TILT, MFAC, LFAC), millimetres (Condylar width, TD, LPD, TT-TG, TT-PCL), percent (PTI) and as an index (CDI). These will be suited by the usage of statistics for interval values.

As the Dejour classification is rated in ordinal variables and the measurements were carried out by two consistent pairs of observers the most suited statistical evaluation is Cohen’s kappa. Therefore, the arithmetic mean between the Cohen’s kappa values of each pair was determined (91).

The remaining parameters are interval scaled variables and also rated independently by two fixed observer pairs. A single MRI was only evaluated by a single rater pair and the other pair assessed a different subset of MRI’s. An Interclass-Correlation (ICC) was carried out to determine observer agreement. The specifications to the ICC according to Hallgren K. (91) are: two-way model, absolute agreement type, single measures and mixed effect (91).

The statistical programme used for the calculation was IBM SPSS – Version 28.0 (IBM Corp., Armonk, NY, United States, 2021) which was provided by the Medical University of Graz. The specifications used were: two-way, mixed effects, absolute agreement and single measures.

The criteria used to judge whether the reliability of Cohen's kappa was good or poor were taken from Landis and Koch (92). Their reference values can be found in the following table:

Result (Cohen's kappa)	Interpretation
0,81-1	Almost perfect
0,61-0,8	Substantial
0,41-0,6	Moderate
0,21-0,4	Fair
0,0-0,2	Slight

Table 5: Interpretation of Cohen's kappa by Landis and Koch (91, 92)

This table provides reference values for the interpretation of Cohen's kappa. A high value for kappa means that the observed disagreement is mostly explained by the true variance between the results and only for a small degree on the errors of measurement between observers (91).

For the judgement of the ICC values the criteria of Cicchetti et al. (93) were applied. The reference values are listed below.

Result (ICC)	Interpretation
0,75-1	Excellent
0,6-0,74	Good
0,4-0,59	Fair
<0,4	Poor

Table 6: Interpretation of the intraclass correlation coefficient by Cicchetti et al. (91)

This table provides reference values for the interpretation of the ICC values. Great inter-rater reliability is demonstrated by high intraclass correlation coefficients. A ICC of 1 stands for perfect agreement, whereas 0 shows random agreement. (91)

In addition to Cohen's kappa and the ICC, the minimal detectable change (MDC) was calculated for the parameters of this study. In general, the MDC value displays the minimal change between measurements to surpass the measurement error. The calculation depends on the desired significance level (94). In this study the confidence threshold which the MDC was calculated with is 95%.

Here the MDC is used to report the smallest change between the measurement of two observers, that can be found statistically significant. This means that a result of a single observer is significanty different from another observer's result when the difference of the two results is greater than the reported MDC. When the difference is smaller than the MDC there is no statistically significant difference between the ratings (95).

The formula used to evaluate the MDC is (94):

$$MDC_{95} = 1{,}96 * \sqrt{(2)} *(SEM)$$

With standard error of measurement (SEM) being calculated by:

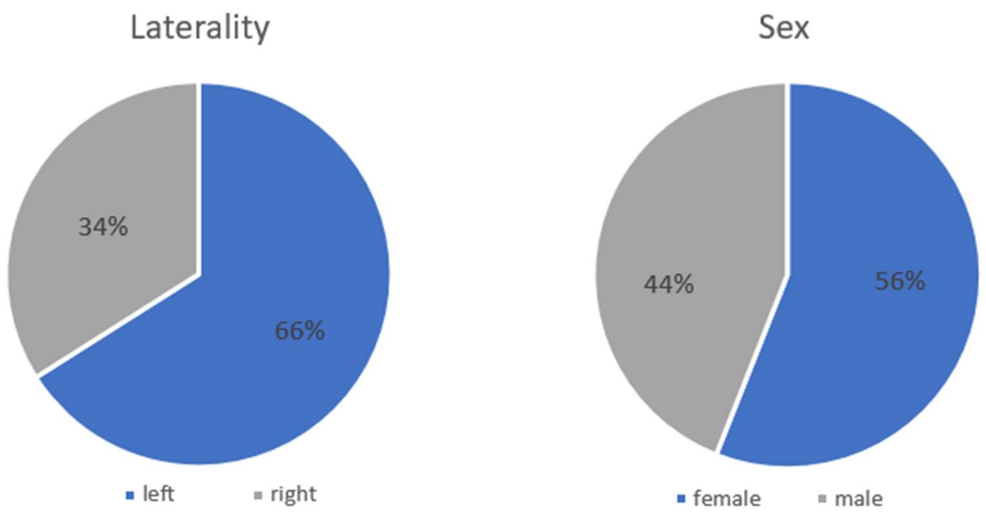
$$SEM = SD * \sqrt{(1\text{-reliability})}$$

SD = standard deviation, reliability = ICC value of the inter-rater reliability

3 Results

3.1 Baseline characteristics

For the determination of the inter-rater reliability 50 patients were randomly selected out of a greater patient sample of 335 patients, who met the inclusion criteria. The descriptive statistics for those 50 patients is provided below.



Laterality	Left	Right	Sex	Female	Male
n	33	17	n	28	22

Figure 16: Distribution of Sex and Laterality

The age of the sample (n=50) is normally distributed and the mean age is 14.724 years. Unfortunately, as the weight of the patients was sourced through the background information of the MR-images it could only be reported for 30 out of the 50 patients. For the not normally distributed data (n=30) the median is 57.5 kilograms. The values for the standard deviation, minimum, maximum and range for weight and age are listed below (Table 7).

	Mean	Median	SD	Min.	Max.	Range
Age (years) n=50	14.724	-	1.873	10.3	17.7	7.4
Weight (kg) n=30	-	57.5	19.1	39	114	75

Table 7: Descriptive statistics of age and weight

This table lists the parameters of descriptive statistics (mean, median, standard deviation, minimum, maximum and range) for age and weight. For age all participants were included into the computation, whereas data for weight was only available for 30 patients.

3.2 Descriptive statistics of the parameters

For a better visualisation of our patient collective the descriptive statistics of the different parameters used in this thesis are provided below. The following table (Table 8) lists the absolute and relative frequency of the different grades of dysplasia according to the Dejour classification. The most frequent type of dysplasia is Grade A. As the patient collective included patients with clinically manifest patellofemoral instability the proportion of high-grade dysplasia (Grade C, D) is high. The distribution shown in this table reflects the assessment of the experienced observers.

Dejour class	N	A	B	C	D
n (50)	15 (30%)	17 (34%)	10 (20 %)	6 (12 %)	2 (4%)

Table 8: Absolute and relative frequencies of the Dejour classes

The following table (Table 9) reports the descriptive statistics for all interval-scaled parameters. The TD, TT-TG and the CDI were not normally distributed, the remaining parameters were normally distributed.

Parameter	Mean	Median	SD	Min.	Max.	Range
Condylar width (mm)	77.3		7.39	65.9	93	27.1
TSA (°)	148.39		9.2	128.3	169.3	41
TD (mm)		3.5	1.2	1.3	6.6	5.3
LTIA (°)	15.49		4.96	3.8	23	23
LPD (mm)	9.05		4.46	1.1	18.6	17.5
FULK (°)	1.25		10.7	-21.4	26.2	47.6
LAUR (°)	0.28		9.89	-19.4	18.4	37.8
TILT (°)	20.51		10.38	1.7	42.9	41.2
MFAC (°)	30.02		10.94	9.1	53.0	43.9
LFAC (°)	23.43		4.4	15.4	38.0	22.6
TT-TG (mm)		11.8	5.15	3.9	24.5	20.6
TT-PCL (mm)	18.87		4.69	8.6	31.4	22.8
CDI		1.3	0.15	0.9	1.7	0.8
PTI	46.94		18.04	8.1	83.71	75.61

Table 9: Descriptive statistics of the parameters for the assessment of patellofemoral instability on MRI

This table lists the mean, median, standard deviation, minimum, maximum and range for all the parameters used in this study. It provides further information on the patient collective. This table is based on the data from the expert observers.

3.3 Inter-rater Reliability

The results of the inter-rater reliability are reported using Cohen's kappa and the ICC.

Cohen's kappa for the standard classification using Grade A, B, C and D as outcomes was 0.785. Applying the criteria established by Landis and Koch (92) this is interpreted as substantial agreement. For the modified Dejour classification Cohen's kappa was 0.824, which can be defined as almost perfect agreement. Both kappa values were statistically significant (p=<0,001). Considered individually the first pair of rater (n=25) achieved a kappa of 0.834. For the second pair a kappa of 0.736 was reported. By using the Dejour classification simplified to high and low-grade, both pairs were able to improve their agreement from 0.834 to 0.92 and from 0.736 to 0.744.

Parameter	Kappa	Kappa (Pair 1)	Kappa (Pair 2)	p	Interpretation
Dejour	0.785	0.834	0.736	<0,001	Substantial
Dejour (high-grade/low-grade)	0.824	0.92	0.744	<0,001	Almost perfect

Table 10: Cohen's kappa for the standard and modified Dejour classification

The Cohen's kappa values for agreement between the observers are listed in this table. The values for all 50 enrolled patients are listed under the category of Kappa. Just as the kappa values for the single pairs of examiners are reported below Kappa (Pair 1/2) for 25 patients per pair. The interpretation refers to the kappa values of all 50 patients.

The parameter assessing trochlear dysplasia are trochlear sulcus angle, trochlear depth and lateral trochlear inclination angle. For the TSA the ICC was 0.759, for the TD 0.702 and for the LTIA 0.826. All values were statistically significant with p<0,001.

The judgement of the noted ICC-values is based on the criteria of Cicchetti et al. (93). This allows the interpretation of excellent agreement for the TSA and LTIA. The TD on the other hand showed good agreement.

Another parameter measured at the distal femur was the condylar width, which showed excellent (ICC: 0.976) agreement.

Parameter	ICC	CI (95%)	p	Interpretation	ICC (Pair 1)	ICC (Pair 2)
Condylar width	0.976	0.957-0.986	<0.001	Excellent	0.981	0.972
TSA	0.759	0.587-0.861	<0.001	Excellent	0.866	0.72
TD	0.702	0.529-0.819	<0.001	Good	0.643	0.708
LTIA	0.826	0.699-0.901	<0.001	Excellent	0.857	0.804

Table 11: ICC values and interpretation of the parameters assessing trochlear dysplasia

The table shows the ICC values, the confidence interval (95%), the p-values and the interpretation for the parameters condylar width, TSA, TD and LTIA. Additionally, the ICC values for the single observer pairs are listed for these parameters. The p-values for of the ICC regarding the individual observer pairs are <0.001.

The lateral patellar displacement, the angle of Fulkerson, the angle of Laurin, the patellar tilt, the medial and lateral facet angle of cartilage are used to value the axial patellar position and morphology. With an ICC of 0.781 the LPD showed excellent agreement. In the same way the ICC values of the FULK (0.914) and the LAUR (0.890) indicated excellent agreement. Excellent reliability was also demonstrated for TILT (ICC: 0,918). In contrast, the ICC value for the MFAC is 0.496, which demonstrated fair agreement. For the LFAC the ICC of 0.723 implied good inter-rater reliability.

Parameter	ICC	CI (95%)	p	Interpretation	ICC (Pair 1)	ICC (Pair 2)
LPD	0.781	0.633-0.872	<0.001	Excellent	0.756	0.717
FULK	0.914	0.853-0.95	<0.001	Excellent	0.872	0.942
LAUR	0.89	0.814-0.936	<0.001	Excellent	0.823	0.945
TILT	0.918	0.859-0.953	<0.001	Excellent	0.884	0.945
MFAC	0.496	0.251-0.68	<0.001	Fair	0.472	0.438 *
LFAC	0.723	0.558-0.832	<0.001	Good	0.833	0.656

Table 12: ICC values and interpretation of the parameters assessing the axial patellar position and morphology

The table shows the ICC values, the confidence interval (95%), the p-values and the interpretation for the parameters LPD, FULK, LAUR, TILT, MFAC and LFAC. Additionally, the ICC values for the single observer pairs are listed for these parameters. If not noted otherwise, the p-values of the ICC regarding the individual observer pairs are <0,001. (* p=0.015)

The parameters used to measure the lateralisation of the tibial tubercle are the TT-TG and the TT-PCL. With ICC values of 0.792 for the TT-TG and 0.725 for the TT-PCL distance the parameters demonstrated excellent (TT-TG) and good (TT-PCL) inter-rater reliability.

Parameter	ICC	CI (95%)	p	Interpretation	ICC (Pair 1)	ICC (Pair 2)
TT-TG	0.792	0.636-0.882	<0.001	Excellent	0.736	0.858
TT-PCL	0.725	0.561-0.834	<0.001	Good	0.206 *	0.806

Table 13: ICC values and interpretation of the parameters assessing the lateralisation of the tibial tubercle

The table shows the ICC values, the confidence interval (95%), the p-values and the interpretation for the parameters TT-TG and TT-PCL. Additionally, the ICC values for the single observer pairs are listed for these parameters. If not noted otherwise the p-values of the ICC regarding the individual observer pairs are <0,001. (* p=0.046)

The ICC values for the parameters used to determine the sagittal patellar position are 0.553 for the CDI and 0.792 for the PTI. Therefore, the measured reliability of the CDI is considered fair, whereas the reliability of the PTI is excellent.

Parameter	ICC	CI (95%)	p	Interpretation	ICC (Pair 1)	ICC (Pair 2)
CDI	0.533	0.303-0.705	<0.001	Fair	0.543	0.538 *
PTI	0.792	0.661-0.876	<0.001	Excellent	0.682	0.886

Table 14: ICC values and interpretation of the parameters assessing the sagittal patellar position

The table shows the ICC values, the confidence interval (95%), the p-values and the interpretation for the parameters CDI and PTI. Additionally, the ICC values for the single observer pairs are listed for these parameters. If not noted otherwise the p-values of the ICC regarding the individual observer pairs are <0,001. (* p=0,02)

3.4 Minimal Detectable Change (95%)

The minimal detectable change (MDC_{95}) for the parameters of this study is reported in the following table. As its value strongly depends on the ICC, those values were listed for a better understanding.

Parameter	ICC	MDC(95 %)
Condylar width	0.976	3.251 mm
TSA	0.759	11.418 °
TD	0.702	1.919 mm
LTIA	0.826	5.693 °
LPD	0.781	5.383 mm
FULK	0.914	8.556 °
LAUR	0.89	8.473 °
TILT	0.918	8.307 °
MFAC	0.496	24.175 °
LFAC	0.723	5.966 °
TT-TG	0.792	6.034 mm
TT-PCL	0.725	7.317 mm
CDI	0.533	0.330
PTI	0.792	24.106

Table 15: MDC Results with their corresponding inter-rater reliability

This table reports the MDC (95%) for all parameters used in this study except for the Dejour classification. The greater the ICC values of the single parameters are, the smaller are the correlating MDC values. This indicates, that the difference in measurements found to be statistically relevant are much smaller for parameters with high inter-rater reliability compared to parameters with low inter-rater reliability.

4 Discussion

The purpose of this study was to demonstrate the inter-rater reliability for several frequently used parameters in the evaluation of patellofemoral instability in a paediatric patient collective. There are multiple pre-existing studies demonstrating the reliability of those parameters in an adult or mixed patient collective. Whether those results are applicable to patients in the growth period is unclear. The following chapter will discuss, whether the reliability of the parameters in a paediatric patient population differs from the reliability in adult patients. In this way, parameters that are particularly suitable for the evaluation of young patients can be identified. However, parameters with a worse reliability than in adults can be advised against.

4.1 Dejour classification

This study found a Cohen's kappa of 0.785 for the Dejour classification, which can be seen as substantial agreement. The Dejour classification is the most commonly used classification system for trochlear dysplasia. However, it is repeatedly criticised for its poor to fair interobserver reliability. Recent studies report a wide range of kappa values for the Dejour classification (96-100). Another complicating factor is that the Dejour classification is now used in various modifications. Some authors rely on a conventional X-ray for classification, others only use an MRI and some combine both modalities. As this study used a solely MRI based approach for the classification the comparison focuses on publications with a similar method.

Other authors using the MRI for classification, who managed to report similar or better reliability than this study are Botchu et al. (97) (0.76-1 Cohen's kappa) and Tscholl et al. (99) (0.873 Cohen's kappa). However, Martinez et al. (96) and Brady et al. (98) (0.13 / 0.289 Cohen's kappa) did report a poorer reliability.

Stepanovich et al. (85) assessed trochlear dysplasia in skeletally immature patients, defined as patient with an open distal femoral physis and found the reliability of the Dejour Classification to be 0.687 (Cohen's kappa) (85). As the distal femur physis closes within the age of 14-17 in females and 15-19 in males (101) their study seems to be the most comparable with the findings of this thesis.

Using approaches different from the MRI based classification Remy et al. (102) found the reliability to be 0.17 (Cohen's kappa) for lateral radiographs in 30° flexion (102). Stepanovich et al. (85) reported a reliability of 0.839 (Cohen's kappa) for lateral radiographs without specification of flexion (85) and Lippacher et al. (100) found a 43% percent agreement for measurements in lateral radiographs in extension (100). The reported reliability for observers using CT and radiographs is 0.510 (Cohen's kappa) (103).

	MRI (CK)	Lateral radiograph (CK)	CT (CK)
Martinez et al. (96)	0.13		
Botchu et al. (97)	0.76-1		
Brady et al. (98)	0.289		
Stepanovich et al. (85)	0.687	0.839	
Tscholl et al. (99)	0.873		
Lippacher et al. (100)	46% (PA)	43% (PA)	
Remy et al. (102)	0.17		
Fritz et al. (103)			0.510

Table 16: Pre-existing data for the reliability of the Dejour classification

This table summarises the different reported reliability values form pre-existing publications. CK = Cohen's kappa, PA = Percent agreement

As shown in Table 16 the Dejour classification seems to have a wide range of reported reliability values throughout all available imaging modalities. As the type of imaging, the procedure of measurement and the criteria for differentiating the types of dysplasia are very different throughout literature, it is not possible to conclude a general assessment of the Dejour classifications reliability (104).

Except for the study of Stepanovich et al. (85) other studies did not exclusively include adolescent or infant patients. The reliability reported by Stepanovich et al. (85) (0.687) is slightly worse than the reliability of this thesis (0.785), but both would be interpreted as substantial agreement. In comparison with the data from mature or mixed patient collectives, which mostly provide poor to fair agreement, this could indicate that the use of the Dejour classification is more reliable in immature than in mature patients. This may be due to different bone to cartilage ratio's in immature knee's (79) or even a decreased influence of muscular stabilisation of the patella in young patients leading to an insufficient or delayed development of osseous and cartilaginous morphology (81).

Another reason for the relatively good reliability outcome might be that Stepanovich et al. (85) created a strict procedure of measurement defining the correct axial plane in which the Dejour classification was applied and proper characteristics distinguishing the different Dejour grades (A-D). The procedure of measurement of this thesis was taken from Stepanovich et al. (85) as we tried to use an already established method for better reproducibility.

Nonetheless, this assertion is contradicted by the fact that studies failed to show significant change in trochlear geometry depending on age (80). Another factor that might influence the results of this thesis is, that the collective used for the determination of the reliability had a relatively high proportion of more severely dysplastic trochleas which could have also facilitated the classification. In contrast to our patient collective with a presence of trochlear dysplasia according to the Dejour classification in 70 percent of the evaluated images (high-grade: 16%), a general population without prior history of patellar dislocation features trochlear dysplasia in only 14.5 percent (high-grade: < 4 %) of the people (105).

It remains unclear, whether this substantial reliability might be reproducible in patients without history of patellofemoral instability or with a different procedure of measurement for the classification. Overall, the approach to grade trochlear dysplasia using the classification from Dejour seems to lack a standardised procedure which could cause the vide variety of different reported reliability scores.

In order to address these issues, the Dejour classification is constantly evolving and it was currently proposed by Dejour et al. (106) to change the Classification from a qualitative grading based on appearance of the trochlear morphology to a quantitative method measuring the sulcus angle, the lateral trochlear inclination and a central bump to classify the dysplasia into low, moderate and high (106). This might be a promising step to improve the obviously inconsistent reliability of the classification in existing literature (85, 96-100, 102, 103).

Nevertheless, this study proved that the Dejour classification, with its substantial reliability, seems to be suitable for the evaluation of trochlear dysplasia in children and adolescents.

4.2 Dejour classification (low-grade/high-grade)

In order to improve the reliability of the Dejour classification a multitude of studies used a simplification from grade A-D to low- and high-grade dysplasia. There is no consent of how the different classes (A-D) should be assigned to low- and high-grade dysplasia. There are different approaches including the definition of Dejour type A as low-grade and B, C, D as high-grade as well as grade A and B as low-grade and C and D as high-grade (102). Both variants achieved different outcomes onto the sought improvement in reliability. Remy et al. (102) reported an improvement in reliability for the A vs. B/C/D type from 0.289 to 0.448 and a decrease for A/B vs. C/D from 0.289 to 0.196 (Cohen's kappa) (102). Others found bigger improvement when using the A/B vs. C/D grading with a change from 46% to 83% percent agreement (100). Tscholl et al. (99) found the best agreement within this variations using the low-grade (A) and high-grade (B/C/D) to be 0.984 (Cohen's kappa) with a slight improvement form their reliability of the original classification (0.873) (99). The classification of grade A and C as low-grade and grade B and D as high-grade exists, but is rather uncommon (107).

This study reported a reliability of 0.824 (Cohen's kappa) for the modified Dejour classification defining grade A and B as low-grade dysplasia and C and D as high-grade dysplasia. This demonstrates an improvement in reliability (from 0.785 to 0.824) compared to the conventional determination of the classification. As a Cohen's kappa value of 0.824 signifies almost perfect agreement the modified Dejour classification seems to be reliable for the evaluation of trochlear dysplasia in patients under 18 years. But it remains questionable, whether the slight improvement in reliability justifies the loss of additional information due to the subdivision into A to D of the original Dejour classification.

4.3 Trochlear sulcus angle

This study found an ICC of 0.759 for the TSA, which is interpreted as excellent agreement. The minimal detectable change was 11.42°. Depending on the interpretation as excellent reliability, it seems that the TSA is very reliably measureable in patients within the growth period. However, considering the MDC of 11.42°, the change of measurement to surpass measurement inaccuracy seems not negligible, especially since the TSA usually varies within a small range of around 130-150°. With a mean TSA of 133,7° in healthy patients and 148,5 in patients with patellofemoral instability (108) the distinction between dysplastic and none dysplastic should be performed with the knowledge of the 11.42° of MDC signalling a potential for measurement inaccuracy.

Our results prove that the TSA is a parameter with excellent reliability for the assessment of trochlear dysplasia. Severe forms of dysplasia can be reliably detected using the TSA. In borderline ranges like 140-145° it should be used with care.

In relation to previously published data our reliability of 0.759 lies within the expected range of 0.69–0.95 (ICC) (55). There is no obvious difference in reliability between adults and patients under 18 years.

4.4 Trochlear depth

The reliability of the trochlear depth with an ICC of 0.702 is interpreted as good. Already reported ICC values for the TD range from 0.69 to 0.93 (55). Stepanovich et al. (85) reported an ICC of 0.928 for immature patients. We were not able to reproduce a comparably good reliability. It seems that the laborious and multi-step measurement might facilitate inaccurate measurement. For adults and mixed patient collectives the reported reliability extends down to 0.69 (ICC) which is also reflected in our results (55). Similar to the TSA the MDC of 1.92 mm imposes another limiting factor. Even in adults the mean value for TD is 3.4 mm (109) and as this parameter is usually even smaller in patients with trochlear dysplasia. The uncertainty of a significant difference in measurement within 1.92 mm seems not optimal for an accurate parameter. Parameters without this problems, like the LTIA, seem to be better suited to evaluate trochlear dysplasia.

4.5 Lateral trochlear inclination angle

The LTIA showed a reliability of 0.826 (ICC) and a MDC of 5,7°. The existing data for the reliability of the LTIA shows a range of 0.39–0.94 (ICC) (55). For the LTIA there are multiple studies that explicitly address immature patients. They reported a wide range of reliability (0.97 (54), 0.944 (85), 0.389 (88) all ICC). When combined with this data our results for infant or adolescent patients proof excellent reliability for this parameter, which means that the LTIA delivers excellent reliability with a relatively small MDC in young patients and is therefore very suitable for the assessment of trochlear dysplasia in this patients. This should be the preferred parameter for quantitative measurement of trochlear dysplasia in patients within growth.

4.6 Condylar width

The condylar width was measured with excellent reliability (ICC: 0.976), which was expected due to the simple process of measurement. This parameter was planned to be used in future studies of my supervisors and therefore included in this thesis.

4.7 Lateral patellar displacement

The LPD is used to describe the axial positioning of the patella and showed an excellent reliability of 0.781 (ICC) and a MDC of 5,38 mm. The previously reported data for the reliability of the LPD includes values of 0.979 (ICC) for mature patients (83) and 0.87 (ICC) for previously operated patients (110). The reduced reliability for patients within the growth period might be due to differences between mature and immature knees. The cartilage content of the lateral condyle, from which the LPD is measured differs between adults and adolescents (79). Furthermore, the overall positioning of the patella within the trochlear groove might be more variable due to much greater joint laxity and reduced muscular stabilisation, which directly affects the LPD measurement (78, 81). Overall, the LPD is still a reliable parameter with a good, but not great value for the MDC, that can be used to describe the axial positioning of the patella for patients within the growth period.

4.8 Angle of Fulkerson/Laurin and Patellar tilt

The angle of Fulkerson, similarly to the angle of Laurin, describes the rotation of the patella in relation to the femur. With an ICC of 0.914 and a MDC of 8.56° the angle of Fulkerson is excellently reliable in adolescent patients. The ICC values of this study are relatively equal to the already reported data for adults (ICC = 0.975) (83).

The test for reliability of the angle of Laurin delivered an ICC of 0.89 with a MDC of 8.47°. As the process of measurement was very similar to the angle of Fulkerson it is not surprising that both show excellent reliability. In accordance with the previously reported data on reliability (ICC of 0.931 (83)) for the angle of Laurin, the interobserver reliability was slightly worse than for the angle of Fulkerson.

The patellar tilt delivered the best results for reliability within the commonly used parameters in clinical practice of this study. The ICC of 0.918 proved excellent inter-rater reliability which is in concordance to the already existing data on reliability (ICC = 0.97 (111)) in patients under 18 years. The remaining reported reliability for the patellar tilt contains values from 0.65 to 0.97 (55). Compared with the wide range of different values for patellar tilt the MDC of 8.3° indicated excellent accuracy of measurement.

Regardless of the possible changes in joint geometry or muscular and ligamentous influencing factors the patellar tilt, the angle of Fulkerson and the angle of Laurin are all suitable for a reliable application in immature patients to demonstrate a potential misalignment of the patella.

4.9 Medial and Lateral Facet Angle of Cartilage

The medial and lateral facet angle of cartilage were used to describe the morphology of the patella. In general, the shape of the patella is highly variable within patients with or without PFI (82). Significant associations between other anatomic risk factors, such as trochlear dysplasia, can be found only for morphological abnormalities of the medial facet of the patella. However, due to the mostly laterally orientated dislocation mechanism, the medial joint facet tends to play a subordinate role in causing instability (82). There is no evidence for any

changes in lateral joint facet morphology to contribute to PFI. Therefore the importance of patellar morphology is rather small (82). The reported reliability for both parameters in adolescent patients is 0.802 - 0.895 (ICC) for the medial facet angle and 0.569 - 0.771 (ICC) for the lateral facet angle of cartilage (82).
In this thesis the reliability of the MFAC was 0.496 (ICC) which is worse than the previously reported data. The big difference in reliability might be caused by the sometimes very irregular shape of the medial cartilage or the high variability of the patellar morphology in general. With a just fair reliability and a MDC of 24.17° within a reference value of 18.8° (82) the MFAC is not reliably applicable to our patient collective.
The lateral facet angle of cartilage on the other hand did show a good reliability of 0.723 (ICC) which corresponds to the pre-existing data. The MDC of 5.97° is considerably smaller than the MDC of the MFAC.

In patients under the age of 18 years the lateral facet angle of cartilage is the favourable parameter for the evaluation of a possible disorder of patellar morphology. Although the reliability is still mediocre and the informative value of this parameter for treatment of PFI is questionable.

4.10 TT-TG

Together with the TT-PCL the trochlear groove to tibial tubercle distance evaluates the lateralisation of the tibial tubercle. As this is a major risk factor for patellofemoral instability and a possible indication for a surgical medialisation of the tibial tuberosity it is important to have a reliable parameter for decision making. The reported reliability for the TT-TG in this study is excellent with an ICC of 0.792 and the MDC is 6.03 mm. A systematic review including 18 studies assessing the TT-TG solely through MRI found the reliability ranging from 0.71 to 0.98 (112), but still only two of the included studies reported data for inter-rater reliability exclusively for immature patients (ICC = 0.85/0.822 (88, 111)). With a few exceptions the reliability generally appears to be somewhat better in adults than in immature patients (112). A reason for the better reliability in adults might be that the TT-TG distance increases with age (113) and therefore is not as susceptible to measurement inaccuracies. Another factor contributing to the decreased reliability might be an enlarged proportion of trochlear cartilage in immature patients (79).

The measurements could therefore be influenced by potential cartilage damage after a dislocation, like irregularities of the cartilage surface or difficulties to identify the correct position of the trochlear groove due to the more prominent cartilage.

A general limitation throughout all age groups is, that the TT-TG is determined by measuring the distance between two landmarks on different sides of the tibiofemoral joint, which could be influenced by rotation in the knee during the imaging process (114).

From the perspective of reliability, the TT-TG proved to be superior to the TT-PCL in children and adolescent patients. Additionally, the TT-TG is the better established parameter and provides a relatively easy procedure of measurement. This could indicate that the TT-TG is the preferable parameter for the evaluation of a lateralised tibial tubercle in adolescent patients.

4.11 TT-PCL

For the tibial tubercle to posterior cruciate ligament distance the reliability was good with an ICC of 0.725 and an MDC of 7.32 mm. Nineteen previously published studies found the ICC within the range of 0.55 to 0.99 for adult or mixed patient collectives in MRI (112). Most of the prior studies on inter-rater reliability did not describe a relevant difference in reliability between TT-TG and TT-PCL (112). A few could find a better reliability for the TT-TG and only one study found the TT-PCL superior to the TT-TG (112). A single study researching the reliability in immature patients found the reliability of the TT-PCL to be 0.533 in contrast to the ICC of 0.822 for the TT-TG. (88) This study’s findings agreed with them as our reliability for the TT-PCL was also worse than the reliability of the TT-TG. In conclusion the TT-PCL seems not to be as reliable as it is in adults and showed reproducibly worse reliability than the TT-TG in children and adolecents.

This conclusion might be limited by the fact, that in comparison of the two rater pairs of this study the TT-PCL delivered very different reliability scores. One rater pair provided a reliability of 0.806, whereas the other pair did only manage to report a ICC of 0.206, which on its own, would be poor reliability. This discrepancy persisted even through repeated and for systematic errors controlled measurements, which indicates that especially for unexperienced observers the TT-PCL determination is difficult and prone to error.

4.12 Caton-Deschamps index

The CDI is, together with the PTI, a well-established parameter for evaluation of patella alta. Both parameters are especially used in immature patients, as they rely on distinct structures even in the growing knee. The ICC of the CDI in this study is 0.533 which blends into the lower end of the spectrum of already reported reliability (ICC 0.41 - 0.96 (55)). The reliability in existing literature for immature patients is 0.96 (111) and the reliability tends to be better in immature patients (115). In this study we could not reproduce those findings. The reliability of the PTI is only fair and the MDC of 0.33 indicates a rather inaccurately reproducible parameter within the established reference values. It remains unclear whether the low reliability is due to the experience of the observers or other factors. A possible reason might be, that Verhulst et al. (116) reported a substantially reduced overall reliability of the CDI when used in MRI compared to X-ray and CT (116). A difficulty might be the identification of the correct sagittal slice in the MR image. With the current reliability of this study, the CDI does not seem to be reliably usable in immature patients, at least with MRI. However, this recommendation is contradicted by the existing data from other studies.

4.13 Patellotrochlear index

The PTI showed an ICC of 0.792, which represents excellent reliability. The MDC of 24.1 appears high, but with a widespread reference range of - 5.0 to 61.1 the MDC is acceptable (58). The reported reliability values for the PTI range between 0.71 – 0.87 (55) and a study solely focussing on immature patients could not be found. Our reliability values fit well into the expected value from recent literature (55). In comparison with the CDI, the PTI seems - not only in our study's findings but also in other papers - to have a better reliability (116, 117). With this in mind, the PTI seems to be the favourable parameter for assessing the sagittal position of the patella in immature patients.

4.14 Influence of the observer experience

One half of the measurements of this study were conducted by two senior medical students and the other half by two residents for orthopaedic surgery. It is hard to measure the impact of the potential lack of clinical experience within the medical students. Both of them went through a proper briefing and did receive a lot of experience by evaluating the parameters listed in this study in approximately 130 to 200 different MR images. All four observers participated in a standardized calibration session, where the precise procedure of measurement was demonstrated in order to ensure consistency in identifying the correct anatomical landmarks.

Some of the results of this investigation were on the lower range within the expected reference data (TSA, TD, TT-PCL, CDI). Some were below (LPD, MFAC). These differences might partly be caused by lack of experience or the fact that some parameters are more difficult to access in patients under the age of 18 than in adults. Studies with high reference values for reliability, such as Ye et al. (83), were mostly carried out by experienced orthopaedic surgeons, therefore it is very likely that our results would indicate better reliability if they were rated with more experience. On the other hand, we did manage to report an above average reliability for the Dejour classification which can be caused by a strict assessment scheme to account for the lack of experience.

4.15 Limitations

The general limitations of this thesis include the age distribution of the enrolled patients. As the mean age is 14,724 years and all included patients are between 10,3 and 17,7 years the results are clearly applicable onto adolescent patients. Due to the lack of patients under the age of 10 years it remains unclear whether the reported reliability is also true for those patients.

Another limitation is that the random sample has been sourced out of a collective of patients with clinically manifest patellofemoral instability. Which means that the proportion of images with severe trochlear dysplasia, patella alta or lateralisation of the tibial tubercle is much higher than in a normal population. Some parameters might be easier or harder to assess in a sample predisposed for changed joint morphology. As an example the medial and lateral facet angle of cartilage of the patella are much more difficult to measure in a severe dysplastic patella than in a normal patella. On the other hand, it is usually easier to distinguish between severe forms of trochlear dysplasia in the Dejour classification due to their prominent features and harder to tell none dysplastic and mild dysplastic trochleas (Dejour A) apart.

This thesis is also limited in its capacity to distinguish between gender specific reliabilities as there was no gender-separated analysis. It might be possible that female patients, especially since females tend to be affected more often than males, differentiate in the expression of their risk factors from their male peers and therefore could show a different reliability of the parameters measuring these risk factors.

A major limitation of this study concerns parameters with a great reported variance throughout literature, especially the Dejour classification. It remains mostly unclear why the results have such a wide spread. A plausible reason might be that a slight deviation from the procedure of measurement, whether on purpose or not, could result in a wide deviation from the reported reliability scores. This means that the results of this study might, to a certain degree be limited to the exact procedure of measurement used in this thesis. For altered approaches to the measurement the reported reliability scores might not apply. This might also influence the reproducibility of our results.

As some of the parameters (Dejour classification, TSA, TD, LTIA, TT-PCL) showed very implausible results in a prior testing for one of the two observer pairings, they received additional training for those parameters and afterwards repeated their measurements to eliminate systematic error. This circumstance might contribute to a greater focus on the right procedure of measurement for those parameters in contrast to the others, which could influence their reliability rating.

4.16 Conclusion

This thesis did manage to provide data in order to select the most suitable and reliable parameters for the evaluation of patellofemoral instability with MR imaging in patients under 18 years. Despite its criticism regarding mediocre reliability throughout literature the Dejour classification proved very reliable for the evaluation of trochlear dysplasia. As a quantitative measurement the lateral trochlear inclination angel is also reliable and accurate for assessing trochlear dysplasia. Regarding the axial position and rotation of the patella all evaluated parameters (LPD, TILT, FULK and LAUR) proved to be reliable. Due to the established usage of the patellar tilt this parameter might be especially useful. The morphology of the patella itself is clinically less important, but when measured, the lateral facet angle of cartilage might be the most reliable way to do so. In accordance with existing literature we found the TT-TG to be more reliable than the TT-PCL and therefore recommend the usage of the TT-TG when evaluating the lateralisation of the tibial tubercle. For evaluation of a potential patella alta the patellotrochlear index is, from a perspective of reliability, substantially better than the CDI and should be preferred within an immature patient collective.

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